CHARACTERIZATION OF RECLAIMED ASPHALT CONCRETE PAVEMENT FOR SASKATOON ROAD CONSTRUCTION

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By

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ABSTRACT

The City of Saskatoon (COS) manages diverse road infrastructure assets. Given the present day challenges of structurally upgrading in-service road infrastructure assets in diverse field state conditions, there is a need to incorporate new innovative materials, changing field state conditions, and mechanistic design methods in sustainable road rehabilitation decision making. The COS is faced with challenges including rising material and labour costs, budget shortfalls, depleting virgin aggregate sources in close proximity to the COS, and an increase in stockpiled asphalt and concrete rubble materials due to transportation infrastructure renewal.

As a result of the COS impact crushing program, a need to determine the design and performance properties of using recycled reclaimed asphalt concrete (RAP) rubble materials in urban pavement structures was established. RAP materials had never been used as a structural base layer in COS pavement structures because no material characterization had been conducted and there was no performance information with regards to their structural behaviour and field performance available. Other jurisdictions documented benefits of using recycled RAP in road structure include: reduced demand on depleting aggregate sources; reduced energy consumption; diversion of stockpiled RAP materials from landfills; and reduced overall handling and disposal costs. Given the amount of crushed RAP material available to the COS, it was determined there are potential benefits to implementing the use of recycled crushed RAP rubble in pavement structures, leading to the implementation of the "Green Street" Infrastructure Program.

The findings of this research indicate that RAP materials have improved mechanistic properties compared to conventional granular materials; therefore, RAP materials can be used as a base layer in a road structure. This research indicates that cement stabilization and cement with a slow setting (SS-1) emulsion stabilization improved the moisture susceptibility of well graded (GW) and open graded base course (OGBC) RAP materials. These findings demonstrated that RAP materials stabilized with cement and/or SS-1 emulsion can be used as a base layer in a pavement structure.

This research also found that the standard Proctor compaction method is not applicable for RAP materials to quantify moisture-density behaviour under compaction, due to the bound-nature of RAP aggregates, which are composed of asphalt and aggregate. California bearing

ratio (CBR) values of Proctor-compacted RAP specimens did not accurately reflect field performance observations.

As part of the COS "Green Street" Infrastructure Program, two test sections using crushed GW RAP rubble materials as a base layer were constructed as part of this research and include Marquis Drive (eastbound lanes from Thatcher Avenue to Idylwyld Drive) and 8th Street East (westbound lanes from Boychuk Drive west 0.540 kilometers). Test sections were constructed by the City of Saskatoon with conventional construction equipment and showed structural improvement in structural performance and visual distresses. Using RAP materials as a base layer was economically feasible because the RAP material cost less than conventional virgin aggregate base materials.

This research demonstrates that processed and crushed RAP rubble materials are technically feasible to be used as a structural base layer in a recycled pavement structural system for urban road rehabilitation systems, and provide economic benefits over conventional granular base materials.

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LIST OF ABBREVIATIONS & SYMBOLS

AASHO – American Association of State Highway Officials
AASHTO – American Association of State Highway and Transportation Officials
ADOT – Arizona Department of Transportation
ASTM – American Society for Testing and Materials
BBA – British Board of Agreement
CBR – California bearing ratio
CIR – Cold in-place recycling
COS – City of Saskatoon
CV – Coefficient of variation
E* – Complex modulus
E_d – Dynamic modulus
ESAL – Equivalent single axle load
FDR – Full depth reclamation
FHWA – Federal Highway Administration
FWD – Falling weight deflectometer
GW – Well graded
HIR – Hot in-place recycling
HMAC – Hot mix asphalt concrete
HWD – Heavy weight deflectometer
LCC – Life-cycle Costs
LDVT – Linear variable differential transducer
LEED – Leadership in Energy and Environment Design
MEPDG – Mechanistic empirical pavement design guide
M_R – Resilient modulus
MC – Moist cured
MDOT – Maine Department of Transportation
MTO – Ontario Ministry of Transportation
NCHRP – National Cooperative Highway Research Program
NDOT – Nevada Department of Transportation
OGBC – Open graded base course
PCC – Portland cement concrete
RAP – Reclaimed asphalt pavement
RaTT – Rapid triaxial tester
SGC – Superpave™ gyratory compactor
SHRP – Strategic Highway Research Program
MHI – Saskatchewan Ministry of Highways and Infrastructure
Superpave™– SUperior PERforming asphalt PAVEments
SS-1 – Slow setting
St.Dev. – Standard deviation
TAC – Transportation Association of Canada
TST – Tube suction test
UK – United Kingdom
UofS – University of Saskatchewan
USA – United States of America

VacSat – Vacuum Saturated
WYDOT – Wyoming Department of Transportation

δ = Phase angle (degrees)
t_i = time lag between cycle of sinusoidal stress and cycle of strain (seconds)
t_p = time lag for a stress cycle (seconds)
ν = Poisson's ratio in X_1 coordinate direction
ε_{11} = Strain in X_1 coordinate direction (axial)
ε_{22} = Strain in X_2 coordinate direction (radial)
ε_{33} = Strain in X_3 coordinate direction (radial)
E_D = dynamic modulus (Pa)
E^* = complex modulus (Pa)
σ_P = applied peak stress (Pa)
ε_P = peak strain response to applied stress (μm/μm)
σ_{11P} = applied peak stress in X_1 direction (Pa)
ε_{11P} = peak strain response to applied stress in X_1 direction (μm/μm)
e = exponent e
I = imaginary component
ω = angular load frequency (radians per second)
t = load duration (seconds)
δ = phase angle (radians)
M_R = Resilient Modulus (MPa)
σ_d = Repeated deviator stress (MPa)
ε_r = Peak recoverable axial strain

CHAPTER 1 INTRODUCTION

As the City of Saskatoon (COS) grows, there is an increased demand for new transportation infrastructure construction combined with the need to rehabilitate existing roads (City of Saskatoon 2008). Urban transportation infrastructure demands impact the need for quality road construction materials in the vicinity of urban centres, particularly quality aggregate sources. This surge of quality aggregate demands is further complicated by an increasing infrastructure deficit over recent years and emerging new infrastructure needs (Mirza 2007). The depletion of natural aggregate resources in the vicinity of many urban centers, including the City of Saskatoon, combined with infrastructure renewal, has resulted in increased material costs and a reduction of readily available quality aggregates for road construction (Taha et al. 1999, Coulter 2003, Berthelot et al. 2004, Anthony 2007, Berthelot et al. 2009a, Berthelot et al. 2010a). This problem has led to concerns with regards to the sustainability of aggregate sources for new road construction and rehabilitation.

Traditional conventional materials used in Saskatchewan road construction are graded aggregate granular base/subbase materials and hot mix asphalt concrete (HMAC) (City of Saskatoon 2005). The costs of road building aggregate materials are increasing due to reduced availability of quality aggregate sources, market demands, and escalating energy costs (Horvath 2003, Berthelot et al. 2007a, Anthony 2007). High quality aggregate sources in Saskatchewan are being exhausted in many regions of the province, particularly in growing urban areas (Marjerison 2000, Berthelot et al. 2004, Anthony 2007, Berthelot et al. 2007a, Berthelot et al. 2009a, Berthelot et al. 2010a). As a result, the cost of quality road construction material sources is increasing significantly due to growing demand and further haul distances.

Presently, the City of Saskatoon reclaims and stockpiles significant volumes of reclaimed asphalt concrete pavement generated from road rehabilitation and/or buried utility rehabilitation operations. The COS generates in excess of 100,000 metric tonnes (MT) of asphalt concrete rubble annually (Berthelot et al. 2009a). In addition, local contractors generate significant quantities of asphalt concrete materials. In the past, limited amounts of stockpiled reclaimed asphalt pavement (RAP) materials were used as low-quality backfill in the COS (Berthelot et al. 2010b).

RAP is defined by the Federal Highway Administration (FHWA) as "removed and/or reprocessed pavement materials containing asphalt and aggregates" (FHWA 2008). RAP materials are typically removed from a pavement structure by surface milling, partial and/or full depth removal, rotomixing, and utility cuts (FHWA 2008). RAP can also be removed by milling the existing HMAC surface; the depth as to which the HMAC is milled varies depending on the required application. This material is also referred to as asphalt millings and is used in hot in-place or cold in-place recycling (Emery 1993).

Although common applications for RAP materials in other jurisdictions include incorporating a percentage of RAP in blended granular base/subbase materials, full depth reclamation, cold in-place recycling, hot in-plant recycling, and hot in-place recycling, there continues to be RAP stockpiled in major urban centers (Emery 1993, Horvath 2003, FHWA 2008). Research has shown that RAP materials removed from a pavement structure often do not achieve specified granular base/subbase gradations and are too high in fines content to be used as a granular base or subbase (Guthrie et al. 2007a, Senior et al. 2008).

The City of Saskatoon stockpiles asphalt millings separately from RAP rubble material retrieved by full depth removal, rotomixing, and utility cuts. The COS has limited uses for RAP rubble material because the stockpiles are comprised of various sized asphalt concrete rubble including large slabs of asphalt concrete, granular materials, and deleterious materials.

Conventional aggregate crushing operations have typically employed jaw and cone type crushing designed for pit run aggregate deposits. In past years, the COS employed conventional jaw and cone crushing to crush RAP rubble. However, when used for crushing stockpiled RAP rubble materials, conventional crushing methods can reduce processing efficiency as well as the quality of the final crushed RAP material product (Berthelot et al. 2009a, Berthelot et al. 2010b). In 2008, the City of Saskatoon commissioned impact crushing equipment specifically designed to crush RAP materials and capable of generating multiple sized materials at once (Berthelot et al. 2010b). Impact crushing stockpiled RAP rubble reduces the technological limitations of conventional crushing equipment: the reduction ratio of the RAP improves, the particle distribution of the RAP material improves, and RAP materials are comprised of more angular, cubical particles and are not stripped of asphalt cement (Garg and Thompson 1996, Berthelot et al. 2009a, Berthelot et al. 2010b).

Various sized crushed RAP materials were generated during the COS impact crushing program, presenting a need to determine the design and performance properties of using these RAP rubble materials in COS pavement structures. RAP material had never been used as a structural base layer in COS pavement structures because no material characterization had been conducted and no performance information with regards to its structural behaviour and field performance was available. However, research shows that the use of RAP materials in road construction reduces demands on depleting aggregate sources, reduces energy consumption, diverts significant amounts of stockpiled RAP materials from landfills, and reduces overall handling and disposal costs (Emery 1993, Garg and Thompson 1996, Bennert et al. 2000, Taha et al. 2002, Horvath 2003, Guthrie et al. 2007a, NCHRP 2008, Widyatmoko 2008). In addition, there are technical benefits achieved by using RAP materials in road construction due to the residual asphalt cement content present in the RAP materials. Therefore, there are benefits to implementing the use of recycled crushed RAP rubble in pavement structures.

1.1 Importance of Research

Demonstrating the use of processed and crushed reclaimed asphalt pavement (RAP) rubble materials as a structural base layer in urban pavements is important to provide more sustainable road infrastructure systems within the COS for several reasons.

- Urban growth in combination with limited infrastructure funding, shrinking quality aggregate sources, and increased conventional road materials and labour costs generate a need for more economically viable transportation infrastructure design and construction solutions.
- The COS generates approximately 100,000 MT of RAP rubble per year from infrastructure rehabilitation projects (Berthelot et al. 2009a, Berthelot et al. 2010b). The amount of RAP rubble generated is anticipated to increase over time given increased demands for infrastructure renewal.

- Of all recycled materials employed within infrastructure assets, RAP can have great economic, environmental, and engineering impact in pavement recycling (Emery 1993, Widyatmoko 2008).
- By deriving a use for RAP rubble materials in new road construction, the COS will divert a significant amount of waste asphalt concrete material from landfills.
- By using stockpiled RAP rubble material in place of quality granular base materials, pressures on locating and transporting depleting aggregate sources would be eliminated and energy would be conserved.
- Due to limited empirical evidence with regards to the field performance of crushed RAP rubble materials as a base layer in road structures, there is a need for the City of Saskatoon to characterize the behaviour of crushed RAP rubble materials for use in pavement systems using mechanistic-based methods.
- Material properties generated from mechanistic-based characterization of road materials are applicable for use in structural modeling and design.
- Environmental considerations have established the need for supporting innovative “green” initiatives in transportation infrastructure design, especially with the potential application of Leadership in Energy and Environment Design (LEED) certification for green infrastructure (USGBC 2008).
- Society’s environmental awareness has increased pressure to design and construct new and innovative infrastructure that incorporates the three pillars of sustainable development: the economy, the environment, and social considerations.
- By using crushed RAP rubble materials within urban road systems, the City of Saskatoon can employ a road recycling program with the end goal of being ‘aggregate neutral’ for internal COS aggregate consumption and public works applications.

The benefits listed above set out a clear direction for this research project. Characterizing the City of Saskatoon’s crushed RAP rubble materials based on fundamental scientific based mechanistic material constitutive properties as a function of Saskatoon’s field state conditions is the first step towards demonstrating the economic, environmental, and social benefits of using RAP in an engineered road system.

1.2 Research Objectives

The objective of this research project was to characterize reclaimed asphalt pavement rubble materials as a structural base layer in City of Saskatoon pavement structures by comparing the conventional and mechanistic behavior of crushed RAP rubble materials across stabilization systems to conventional granular base material under realistic field state conditions.

1.3 Research Hypothesis

The hypothesis of this research was that processed and crushed RAP rubble materials are technically feasible to be used as a structural base layer in a recycled pavement structural system for urban road rehabilitation systems in Saskatoon. It was also hypothesized that recycled asphalt pavement road materials would provide economic benefits over conventional granular base materials in Saskatoon.

1.4 Research Scope

Materials considered in this study included crushed RAP rubble materials sampled from the City of Saskatoon Nicholson Yard stockpile processed in 2008 and 2009 to a well graded (GW) and open graded base course (OGBC) gradation. The experimental program included conventional physical aggregate property tests as specified by the City of Saskatoon, American Society for Testing and Materials (ASTM), and American Association of State Highway Transportation Officials (AASHTO), and triaxial frequency sweep characterization. Triaxial frequency sweep material properties including dynamic modulus, phase angle, Poisson's ratio, and radial microstrain behaviour were characterized across four load frequencies and four triaxial stress states representative of typical City of Saskatoon field state conditions at 20ºC. Triaxial frequency sweep testing can be conducted at various temperatures; this study is limited to a testing temperature of 20ºC.

A preliminary strengthening analysis across 2008 GW and OGBC COS crushed RAP rubble materials using one percent, two percent, and three percent slow setting (SS-1) emulsion stabilization, cement (type 10) stabilization, and cement/SS-1 emulsion stabilization (50/50 split) was conducted to assess the effect of stabilization of crushed RAP rubble materials. Based on the 2008 preliminary strengthening analysis, selected stabilization systems were used to strengthen samples of 2009 crushed, processed, and stockpiled City of Saskatoon reclaimed asphalt pavement materials (including GW and OGBC gradations).

Climatic durability evaluation included vacuum saturation testing and triaxial frequency sweep testing on the 2009 GW and OGBC reclaimed asphalt pavement rubble materials strengthening systems. The testing program was limited to five (5) replicate samples due to time and resource limitations. Since testing more than five samples may have provided more statistically meaningful results, statistical analysis is limited in this investigation to average, standard deviation, and coefficient of variance.

Two test sections using crushed GW RAP rubble materials as a base layer were constructed by City of Saskatoon forces (sections of Marquis Drive and 8th Street East). The City of Saskatoon conducted non-destructive heavy weight deflection testing to evaluate the structural performance of the rehabilitated pavement systems. An economic evaluation comparing the capital cost of using conventional granular base aggregates versus crushed RAP rubble materials as base aggregates is included.

1.5 Layout of Thesis

Chapter 1 provides the introduction and significance of the work undertaken in this research. This section also includes the goal, objectives, scope, and methodology for this work, as well as the layout of the thesis. Chapter 2 summarizes the background information and literature relevant to this thesis. Information with regards to various RAP systems and use of RAP in the COS are discussed. Also, a description of mechanistic material characterization is provided in Chapter 2. Chapter 3 details the experimental program and methodology followed in this research.

Chapter 4 reports the laboratory characterization of the 2008 RAP. Chapter 5 Chapter 5 reports the laboratory characterization of the 2009 crushed reclaimed asphalt pavement rubble. Chapter 5 also briefly summarizes the construction of the test sections by the City of Saskatoon. Chapter 6 presents the summary, conclusions, and recommendations based on the results of this study.

CHAPTER 2 LITERATURE SEARCH

This chapter summarizes background information and the findings of literature relevant to this thesis. A description of conventional pavement design and rehabilitation is provided. Information of reclaimed asphalt pavement (RAP) materials pertinent to this research described herein include: history and background of recycling RAP in road construction; benefits and limitations of using recycled materials in road construction; RAP materials testing and use of strengthening systems; and design, constructability, specifications, and performance of recycled materials in roads. Background information of City of Saskatoon conventional pavement structures is provided. City of Saskatoon challenges related to its transportation infrastructure and materials are summarized.

2.1 Conventional Pavement Design and Rehabilitation

The majority of Saskatchewan's roads are constructed as flexible pavement structures comprised of a hot mix asphalt concrete (HMAC) surface, granular base layer, and granular subbase or drainage rock layer placed on *in situ* subgrade. Figure 2.1 illustrates a typical City of Saskatoon (COS) urban cross section. City of Saskatoon's pavement structure layers can vary. Ageing pavement structures in the COS's older neighborhoods are often comprised of only a granular base layer and HMAC surfacing on top of subgrade.

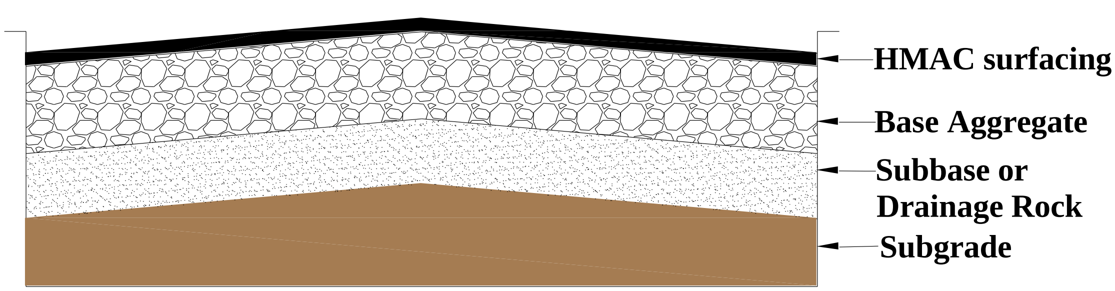


Figure 2.1 Typical City of Saskatoon Pavement Structure Cross Sections

Pavement performance depends on the behaviour of granular base materials when subjected to moisture infiltration (Cote and Konrad 2003, Syed et al. 2000). Moisture infiltration in a granular base affects the stiffness and strength of a pavement structure and can result in permanent deformation or failure of a pavement structure (Cote and Konrad 2003, Syed et al. 2000). Granular bases are also affected by climatic effects caused by moisture content and seasonal freeze-thaw cycles. In the winter, water within the pavement structure freezes, increasing the load-carrying capacity of the road and sometimes resulting in differential frost heaving due to the formation of ice in the granular base layer (Zubeck and Dore 2009, Cote and Konrad 2000, Berthelot et al. 2008a). In the spring, the frozen pavement structure thaws, causing weakness in the granular base layer and subgrade, and decreasing the load-carrying capacity of the road (Berthelot et al. 2008a, Cote and Konrad 2000). Moisture influences the performance of granular base materials in a pavement structure. To mitigate moisture problems and wetted-up subgrades, roads in Saskatoon subject may be constructed with a drainage rock subbase (Prang 2010).

Saskatchewan HMAC pavements are considerably thinner than Canadian and United States of America (USA) counterparts primarily due to Saskatchewan's lower traffic volumes and budget constraints (Berthelot et al. 2008a). In the City of Saskatoon, HMAC surface thickness depends on road classification; for example, local roads may have 50 mm HMAC where arterials may have 100 mm HMAC. Freeways are constructed with up to 200 mm HMAC surfacing (COS 2008a)

2.1.1 Empirical Design Approach

Saskatchewan's highway network was designed based on the *American Association of State Highway Transportation Officials (AASHTO) Guide for Design of Pavement Structures* (1986). This design method uses the cumulative number of 80 kN equivalent single axle loads (ESALs) for the design life of the pavement structure and is based on load equivalency factors that were determined during the American Association of State Highway Officials (AASHO) Road Test in Ottawa, Illinois in the 1960s. The AASHO Road Test concluded that the effect of commercial trucks on pavement performance could be determined by the number of 80 kN single axle loads or their equivalency (AASHTO 1986).

When applied to Saskatchewan field state conditions, several limitations of the ESAL-based pavement design and performance prediction method exist. Firstly, Saskatchewan's commercial traffic loading, pavement structures, and environmental conditions are significantly different from the inference of the AASHO Road Test, upon which ESALs were developed. Furthermore, the values established in the *AASHTO Guide for Design of Pavement Structures* were considered to be the best available technical approach to pavement design at the time – over 50 years ago (1986). At the time of the AASHO Road Test, limited knowledge existed regarding the long term performance of pavement structures, particularly with regards to ageing road structures and the relationships between damage loading and climatic conditions. Given Saskatchewan's severe climatic conditions and ageing infrastructure, reliance on AASHO Road Test ESAL formulations alone can be misleading for pavement structure life cycle performance prediction in Saskatchewan. This pavement design methodology is dependent on the design life ESALs, *in situ* subgrade type, the materials used to construct the pavement structure, and is specifically related to the California Bearing Ratio (CBR) Shell Design Curves (AASHTO 1986).

AASHTO's design guide and the CBR Shell Design Curves predominantly rely on empirical approaches and correlations to pavement performance for pavement design. These methods of pavement design rely on standardized traffic loadings and physical properties of materials estimated from the AASHO Road Test field study that took place over 50 years ago (AASHTO 2002). Empirical pavement design methods do not account for the realistic field performance of road materials (Ali 2005). AASHTO's *Guide for Mechanistic-Empirical Pavement Design of New and Rehabilitation Structures* (2002) presents a pavement structure design method that accounts for the effects of changing field state conditions (traffic loadings and environmental conditions) on the structural response and performance of a pavement structure.

2.2 RAP Systems Background

Reclaimed asphalt pavement (RAP) has been used in transportation construction for over 40 years in both the United States of America (USA) and Canada (Emery 1993, FHWA 2008). RAP materials are typically removed from a pavement structure by surface, partial-depth, or full depth removal, rotomixing, or utility cuts (FHWA 2008). Depending on the size of the removed RAP, RAP can be further processed, crushed, and screened for use in hot and cold recycling processes. Recycling RAP has not become consistent, regular practice in transportation jurisdictions and agencies across Canada and USA, where in some instances RAP is disposed of in landfills or stockpiled indefinitely (Emery 1993). A number of hot and cold recycling processes using RAP exist and are listed and summarized in the Federal Highway Administration (FHWA) *User Guidelines for Byproducts and Secondary Use Material in Pavement Construction* (2008).

This section provides an overall summary of hot and cold recycling processes using RAP, including the following technologies: hot mix plant recycling, hot in-place recycling, full depth reclamation, cold in-place recycling, and as blended granular material. Research experience has indicated that asphalt recycling using these processes is both economical and practical from a technical standpoint (Emery 1993, Issa et al. 2001, Karlsson et al. 2006).

2.2.1 Hot Mix Plant Recycling

Hot mix plant recycling is the most common type of asphalt recycling in Canada and the USA (Emery 1993, Sullivan 1996). Hot mix plant recycling is the process of adding RAP in batch, drum, and drum-batch hot mix plants to produce HMAC for surface or binder courses (Emery 1993). RAP used in hot mix plant recycling is retrieved by milling old asphalt pavement and can be taken from various sources; however, adequate mixing between sources and stockpiles is required to achieve a homogeneous RAP product that meets an agency's specified gradation (Emery 1993, Sullivan 1996). Emery (1993) describes the following requirements to ensure a high-quality recycled hot mix: Marshall mix design for representative materials; consistent RAP gradation; asphalt cement grade to ensure satisfactory in-place penetrations; good hot mix plant production; producer quality control; and agency quality assurance. It has been proven that recycled hot mix asphalt pavement can have at least the same quality and physical characteristics as conventional HMAC (Emery 1993, Sullivan 1996, Hossain et al. 1993, Widyatmoko 2008, Duclos and MacKay 2009).

The addition of RAP to HMAC mixes is permitted in all Canadian provinces with the exception of Nova Scotia and Prince Edward Island (Duclos and MacKay 2009). The permissible amount of RAP allowed in each Canadian province for hot mixes also varies. For example, Alberta allows up to 30 percent RAP in hot mixes, Saskatchewan allows up to 20 percent RAP in its asphalt mixes, and the City of Saskatoon allows up to ten percent RAP in two of their HMAC mixes (Prang 2008, Anthony 2008, Duclos and MacKay 2009). Although transportation agencies' specifications may allow for a percentage of RAP in virgin mixes, RAP is not necessarily used in all HMAC work (Emery 1993, Prang 2008, Anthony 2008). For example, in 2008, Saskatchewan Ministry of Highways and Infrastructure (MHI) estimated that only ten percent of total asphalt mixes contained RAP (Anthony 2008).

In the USA, hot mix plant recycling is considered standard practice and Sullivan (1996) found that 45 million tonnes of RAP are generated annually in the USA and 33 percent of that RAP is used in hot mix production. In the USA, the RAP content permissible in hot mix plant recycling is determined by the state highway agency (Sullivan 1996). RAP limitations in the USA vary from state to state. For example, the state of Arizona allows up to 40 percent RAP in its binder course and no amount of RAP in its surface course (Sullivan 1996). The state of Oregon allows 20 percent RAP in both its binder and surface courses (Sullivan 1996).

In the United Kingdom (UK), Widyatmoko (2008) investigated the mechanical performance of asphalt mixtures containing 10 percent, 30 percent, and 50 percent RAP using laboratory tests and found that the asphalt mixtures containing RAP performed at least or better than conventional asphalt mixes. Widyatmoko (2008) found that the stiffness of samples containing RAP was slightly lower than conventional asphalt mixes and that the RAP samples had a lower resistance to permanent deformation. However, the stiffness and resistance to permanent deformation was deemed acceptable for the UK (Widyatmoko 2008). Fatigue resistance of the samples containing RAP was found to be at least equally to or better than conventional asphalt mixes. Also, samples containing RAP were least susceptible to moisture induced damage overall (Widyatmoko 2008).

The Arizona Department of Transportation (ADOT) constructed experimental recycled and conventional asphalt concrete overlays in 1981 on a highway project. Prior to this experimental project, ADOT had been constructing recycled asphalt concrete pavements since the late 1970s (Hossain et al. 1993). The recycled overlay was comprised of 50 percent RAP added in hot mix plant production (Hossain et al. 1993). Following ten years in-service, the performance of the recycled and conventional asphalt concrete overlays were evaluated using a visual distress survey and falling weight deflectometer measurements. The performance of the recycled asphalt concrete overlay was comparable to the conventional asphalt concrete overlay after ten years (Hossain et al. 1993). In terms of rutting, in this case, the recycled asphalt mix performed better than the conventional asphalt mix.

Although using RAP in hot mix plant recycling is standard practice across most of Canada and USA, some limitations to this process exist. Using a high percentage of RAP in binder and surface courses is limited to asphalt mixes with low volume traffic as RAP mixes can have a lower resistance to rutting and permanent deformation (Emery 1993, Widyatmoko 2008). The fines content in RAP material can pose stability problems with recycled hot mix design with regards to generating voids; control of the gradation and fines content is recommended (Emery 1993, Widyatmoko 2008). The aged binder in the RAP can be hardened due to age, requiring the addition of a softer binder to soften the aged binder in the RAP (Widyatmoko 2008). The use of RAP in hot mix is also limited by a lack of hot mix asphalt plants equipped for the addition of RAP into the hot mix (Duclos and MacKay 2009).

The use of RAP in hot mix is standard practice in most Canadian and USA jurisdictions (Emery 1993, Sullivan 1996, Duclos and MacKay 2009). Laboratory research and field performance testing has shown that recycled hot mix incorporating RAP can perform equivalent to conventional hot mix (Emery 1993, Sullivan 1996, Hossain et al. 1993, Widyatmoko 2008, Duclos and MacKay 2009). Economics do not pose a limitation to the use of RAP in hot mix plant recycling (Emery 1993). Using RAP in hot mix plant production reduces the use of virgin material (Widyatmoko 2008).

2.2.2 Full Depth Reclamation

Full depth reclamation (FDR) is an in-place road recycling technique that involves removing the aged asphalt pavement layer and a portion of the underlying base or subbase material, rotomixing these layers together, stabilizing the remixed material if required, placing and compacting, and surfacing with a HMAC overlay. FDR is typically performed to a total depth of 100 mm to 300 mm and often involves stabilization of the remixed material using cement, asphalt emulsion, fly ash, or lime (Emery 1993, Kearney and Huffman 1999, Mallick et al. 2002).

FDR is an in-place recycling rehabilitation solution for pavement structures that are structurally poor. FDR provides environmental advantages in terms of reduced gas emissions, reduced fuel consumption, and minimized need for virgin aggregates (Emery 1993, Kearney and Huffman 1999, Mallick et al. 2002, Guthrie et al. 2007b, Berthelot et al. 2009b, Jeon et al. 2009). Furthermore, FDR addresses structural deficiencies in a pavement structure and can provide a granular base that has improved performance over typical granular material. FDR is also cost-effective in terms of construction time, construction costs, maintenance costs, and overall long-term costs (Mallick et al. 2002, Berthelot et al. 2009b, Berthelot et al. 2008b). FDR is common in the USA and has been implemented in various projects across Canada, including the City of Saskatoon (Emery 1993, Kearney and Huffman 1999, Mallick et al. 2002, Guthrie et al. 2007b, Berthelot et al. 2009b).

Mallick et al. (2002) conducted a laboratory study of New England FDR mixes. The Maine Department of Transportation (MDOT) was aware of the benefits of FDR and had already constructed various FDR projects in the state (Mallick at al. 2002). The objectives of the study were to identify a proper mix design procedure for determining the amount and type of additive to add for specific locations in Maine (Mallick et al. 2002). Based on the results of this study, it was recommended that more field test sections be constructed to evaluate the performance of emulsion, lime, and cement additives to FDR materials (Mallick et al. 2002).

In 1999, MHI constructed FDR test sections on Control Section (C.S.) 19-06 in Saskatchewan to evaluate the long-term performance of FDR stabilized pavement systems in a northern climate (Berthelot and Gerbrandt 2002). This project was considered a pilot project and involved the reclamation and stabilization of *in situ* subgrade materials to strengthen Saskatchewan rural thin pavements. Test sections constructed included flyash or cement stabilized subgrade with or without granular base material; a double-seal surface course was placed. A conventional double seal pavement system was constructed for comparison purposes. After two years of in-field service, it was found that the cement and flyash stabilized roads were performing well (Berthelot and Gerbrandt 2002). The results of the visual distress survey showed that the stabilized subgrade with granular base and seal structures were showing minimal distresses, whereas the stabilized subgrade with seal was showing moderate to severe edge and substructure failures. Both conventional Benkelman beam surface deflection measurements and the HWD deflection measurements were found to be considerably less for the cement-stabilized subgrade system when compared to the conventional pavement system (Berthelot and Gerbrandt 2002). MHI found that stabilized FDR provides an *in situ* road recycling process that provides a "technical and economically feasible solution for strengthening Saskatchewan thin-paved roads" (Berthelot and Gerbrandt 2002).

In 2007, in the City of Saskatoon, a portion of Idylwyld Service Road was structurally upgraded using FDR as the recycling process because Idylwyld Service Road was structurally poor (Berthelot et al. 2009b). This FDR project incorporated cement-emulsion stabilization with the pulverized asphalt cement and granular base material. Based on post construction non-destructive HWD measurements, FDR provided "improved climatic and mechanistic performance of *in situ* reused materials, improved long term performance of the structural system, reduced weather exposure, and minimized risks due to increasing construction costs relate to construction capacity and energy prices" (Berthelot et al. 2009b).

Although FDR provides numerous advantages, there are a few limitations to the use of FDR for pavement rehabilitation. FDR construction requires warm, dry weather conditions; construction cannot be carried out during rain, high humidity, or fog (Kearney and Huffman 1999). The long term climatic effects of FDR are varied due to *in* situ material variability (Berthelot and Gerbrandt 2002, Mallick at al. 2002). FDR with stabilization is limited because curing time is required during which no heavy trucks or construction equipment should be subjected to the FDR surface. Also, FDR requires a surfacing treatment such as a seal coat or a hot mix asphalt surfacing.

2.2.3 Hot In-Place Recycling

Hot in-place recycling (HIR) is a method of recycling in-place hot mix asphalt concrete (HMAC) to correct pavement distresses. Roads suitable for HIR should be in adequate structural condition. HIR requires a specialized train of equipment. HIR is carried out by softening the existing asphalt surface to a depth of up to six inches, milling it, mixing it with new asphalt binder, virgin aggregate, and, in certain projects, a stabilizing agent such as a rejuvenator, and placing and compacting the HIR material (Sullivan 1996). A HMAC overlay is placed as a wearing surface on top of the compacted HIR material. HIR has been increasingly used since the 1980s, with numerous HIR projects constructed in Canada in the 1990s (Terrel et al. 1997). Over the years, the technology and equipment associated with HIR has become standardized.

There are three basic HIR processes: heater-scarification, repaving, and remixing (Terrel et al. 1997, Duclos and MacKay 2009). Heater-scarification is also called ‘surface recycling’ and does not involve the addition of a rejuvenator; this type of HIR corrects a road’s profile. Repaving requires the addition of a rejuvenator, virgin aggregates, or hot mix asphalt to improve the pavement surface. Remixing also requires the addition of a rejuvenator, virgin aggregates, or hot mix asphalt to improve a pavement surface that is “severely deformed” (Duclos and MacKay 2009). Benefits to HIR include economic savings and fair to good long-term performance (Emery 1993, Terrel et al. 1997).

Between 1987 and 1999, the Ontario Ministry of Transportation (MTO) completed over 80 projects using the HIR process (Kazmierowski et al. 1999). A 10-year performance review of the HIR projects by MTO revealed that the HIR pavements were performing comparably to conventional pavements (Kazmierowski et al. 1999). Overall, cracking in HIR pavement met the pavement condition criteria set for HIR pavements. Since beginning using HIR in Ontario, MTO has observed continual improvements in HIR construction equipment and performance specifications (Kazmierowski et al. 1999). Saskatchewan Ministry of Highways and Infrastructure (MHI) had planned to execute a trial HIR project on a primary highway in summer 2012, but had not begun the work at the time of this thesis’ publication (Anthony 2010).

There are many concerns and limitations associated with HIR. Primarily, HIR is applicable to remediating surface distresses only and does not repair structural problems. There are also concerns with the finished surface of the HIR pavement; adequate compaction, segregation, cracking, and smoothness are all issues HIR pavements frequently experience (Terrel et al. 1997). Also, there is often a loss of the pavement surface's resistance to water damage due to stripping. HIR is not functional for urban road rehabilitation due to the length of the HIR paving train (Terrel et al. 1997).

2.2.4 Cold In-Place Recycling

Cold in-place recycling (CIR) is a method of recycling in-place HMAC by milling and placing it as a cold-mix for surface rehabilitation purposes. Roads suitable for cold in-place recycling should be in fair to good structural condition with primarily surface deterioration; CIR, like HIR, rehabilitates the asphalt pavement surface and not the road sub-structure (Emery 1993). Although low volume roads were initially considered for CIR, medium and higher volume roads are now rehabilitated with CIR (Gerbrandt et al. 2000, Duclos and MacKay 2009).

The CIR process involves a cold in-place recycling train consisting of a cold-milling machine that reclaims the aged asphalt pavement to a certain depth, a screening and crushing unit, a mixing unit for the addition of water and/or a stabilizer, a paver unit to place the recycled cold mix, and compaction equipment. A HMAC overlay is typically placed as a wearing surface. Emery (1993) states "pavement designers generally assign a higher structural strength to recycled cold mix than granular base." Additional benefits of cold in-place recycling include removing surface distresses from the asphalt pavement, deferring reflective cracking, reducing fuel usage, reducing gas emissions, and an overall reduction in energy requirements (Gerbrandt et al. 2000, Sebaaly et al. 2004). There are no standard design procedures for CIR and there is limited long-term performance information available regarding the performance of CIR pavements (Kazmierowski et al. 1999, Sebaaly et al. 2004). However, cold in-place recycling is common in the USA and has been implemented in various projects across Canada (Gerbrandt et al. 2000, Duclos and MacKay 2009).

The Ontario Ministry of Transportation (MTO) has seen an increase in the amount of CIR projects carried out in Ontario since 1989; 300,000 m^2 of CIR work was conducted in 1987 and 2,000,000 m^2 of CIR work was conducted in 1997 (Kazmierowski et al. 1999). Stabilizers used in CIR processes in Ontario include emulsions, quicklime, and cement slurry with emulsion.

MTO found that, through pavement distress surveys and pavement deflection analysis, CIR pavements increase in strength with curing. MTO also established that CIR pavements must be overlaid with a HMAC surface treatment (Kazmierowski et al. 1999). Overall, MTO found the performance of CIR, when overlaid with an HMAC surface, to be comparable to conventional HMAC.

The Nevada Department of Transportation (NDOT) has experienced much success with using CIR on its low and medium volume roads (Sebaaly et al. 2004). In 1997 and 1998, laboratory and field testing was carried out to validate CIR mix design processes and long-term field performance. CIR mixes included the addition of a lime stabilizer to improve the moisture sensitivity of the material. Prior to construction, resilient modulus testing was conducted to determine the resilient modulus of the CIR mixtures. Cores of the CIR field test sections were retrieved four year post construction. A wide range of resilient modulus values were measured for the cores at two test sections, indicating that the CIR pavement had not aged uniformly with time (Sebaaly et al. 2004). The cores for a third test section could not be tested for resilient modulus. A comparison of the mix design samples and the field cored samples showed comparable results (Sebaaly et al. 2004). The visual distress survey found that at all three test sections, rutting was moderate and minimal to no cracking distresses were observed. Based on this research, NDOT continues to recommend CIR with the addition of lime as an effective rehabilitation treatment for low and medium volume roads (Sebaaly et al. 2004). The results of laboratory and field testing showed that CIR reduces cracking and rutting in rehabilitated pavements and prompted NDOT to construct additional CIR projects (Sebaaly et al. 2004).

Since CIR is limited to surface rehabilitation, it provides many advantages for the remedy of pavement distresses (Gerbrandt et al. 2000, Sebaaly et al. 2004). Pavement distresses such as rutting and cracking are removed during the CIR process and there is a reduction in reflective cracking through the new HMAC layer. Pavement ride and grade lines are also improved. The addition of stabilizers including cement, emulsion, or lime to the CIR mix can result in increased strength with appropriate curing time (Kazmierowski et al. 1999, Gerbrandt et al. 2000, Sebaaly et al. 2004). Emphasis on agencies establishing laboratory mix design procedures and field performance test sections is highlighted in much of the literature (Emery 1993, Kazmierowski et al. 1999, Gerbrandt et al. 2000, Sebaaly et al. 2004).

CIR is not applicable to pavement structures with poor drainage and is limited to pavements with asphalt mat surface distresses. Like FDR, CIR can only be used in warm, dry weather. Similar to HIR, CIR requires a long train of equipment to carry out the construction process. This is not suitable for urban applications. Some issues with constructability have been identified (Gerbrandt et al. 2000, Kazmierowski et al. 1999). For example, CIR requires milling a predetermined depth of existing HMAC surface. If the existing HMAC surface varies in depth and is not consistent, then some granular base may be mixed in with the CIR material during milling, resulting in variability of the reclaimed HMAC. Also, CIR pavements are susceptible to moisture intrusion and abrasion (Kazmierowski et al. 1999). In Saskatchewan, where a number of seal coat granular structures exist, CIR cannot be applied to thin granular pavements (Gerbrandt et al. 2000).

2.2.5 Blended Granular Materials

Using RAP in blended granular material involves adding a percentage of RAP to virgin aggregate base or subbase materials. Numerous studies have shown that although the addition of up to 50 percent RAP to granular material is beneficial, performance results depend on the crushing technique used to process and crush the RAP, and the laboratory tests used to evaluate the performance of the RAP blended granular material (Coulter 2003, Guthrie et al. 2007a, Kim et al. 2009, MacGregor et al. 1999, NCHRP 2008). Using RAP in blended granular material is different from FDR such that RAP is added to virgin or reclaimed granular base or subbase material in-place.

Coulter (2003) reported that the Ontario Ministry of Transportation (MTO) is the only jurisdiction in Canada that "fully defines the criteria for the use of RAP in a granular base or subbase." Presently, MTO allows the addition of up to 30 to 40 percent RAP in granular base courses given the blended granular material physical and gradation specifications are met (Emery 1993, MTO 2003, Senior et al. 2008). An observed decrease in California bearing ratio (CBR) strength occurs as the RAP content of a blended granular base is increased (Emery 1993, Senior et al. 2008). However, field performance indicates that MTO's blended granular material incorporating RAP has performed well over the years (Senior et al. 2008).

Garg and Thompson (1996) conducted a laboratory and field investigation study of the use of RAP in base layers. A field test section in Illinois was constructed using two layers of RAP base material and overlaying with a HMAC surface. RAP materials were retrieved during construction and underwent laboratory testing. Gradation testing indicated that the gradation of the RAP lacked fine materials passing the number four sieve (4.75 mm) and differed from conventional base aggregate gradation specifications (Garg and Thompson 1996). Falling weight deflection (FWD) measurements taken post construction indicated that the RAP base layer test sections were performing comparably with conventional base layer test sections (Garg and Thompson 1996). The visual distress survey indicated only minor rutting and no cracking.

There is a significant amount of literature detailing the laboratory testing of varying amounts of RAP blended with granular base or subbase aggregates. Various laboratory tests are used depending on the study. These tests are discussed further and in more detail in proceeding sections. With regards to stiffness of RAP-blended granular materials, MacGregor et al. (1999) and Kim et al. (2007) indicated there was a general increase of resilient modulus with an increase in RAP content. Whereas Kim et al. (2007) determined that the stiffness of the 100 percent RAP sample was equivalent to the stiffness of the 50 percent RAP 50 percent virgin aggregate sample, MacGregor et al. (1999) found the 100 percent RAP samples had a higher resilient modulus and stated that the "test results clearly show the stress-hardening nature of this material". With regards to California bearing ratio (CBR) of RAP-blended granular materials, Taha et al. (1999) and Guthrie et al. (2007a) indicated there was a decrease in CBR with an increase in RAP content. Particle distribution and gradation of the RAP-blended materials were found to influence the behaviour and performance of the blended granular materials (Guthrie et al. 2007a, Kim et al. 2007, MacGregor et al. 1999, Taha et al. 1999).

Although the addition of RAP to blended granular material is generally considered to be beneficial, using RAP blended granular materials in a pavement structure is limited primarily to a lack of laboratory testing and field performance data (Garg and Thompson 1996, Guthrie et al. 2007a, Kim et al. 2007, MacGregor et al. 1999, Taha et al. 1999). Using RAP in blended granular material is also limited based on the source of the RAP and the crushing operations used to crush it (Garg and Thompson 1996). There are few established specifications for blended granular materials; most jurisdictions do not employ any specification for blended granular materials.

2.2.6 Embankment or Fill

RAP material can also be used as embankment, fill, or for highway shoulder applications. For instance, MHI allows up to 80 percent RAP for shoulder applications (Anthony 2008). MHI employs standard specifications for stockpiling RAP material; however, there are no standard test procedures required to assess the mechanical properties of RAP materials for use as embankment, fill, or shoulder applications. This is not the most beneficial use of RAP material as these applications do not make use of RAP material's high-value recovered binder and aggregate (FHWA 2008, Duclos and MacKay 2009).

2.3 Use of Stabilizers in RAP Systems

Pavement designers can structurally improve soils and aggregates using stabilizers. Stabilizers such as lime, cement, asphalt emulsion, and fly ash are used in RAP systems to enhance material properties, moisture susceptibility, and field performance (Emery 1993, Berthelot and Gerbrandt 2002, Berthelot et al. 2007a, Berthelot et al. 2009b, Guthrie et al. 2007b, Kearney and Huffman 1999, Xu and Berthelot 2010). For example, lime is typically added to Saskatchewan hot mixes, including hot mix plant recycling, as an anti-strip (Berthelot et al. 2010c). FDR typically employs lime, cement, asphalt emulsion, or fly ash stabilization of remixed material (Emery 1993, Kearney and Huffman 1999, Mallick et al. 2002). HIR typically employs a rejuvenator and CIR uses stabilization systems similar to those of FDR.

The addition of cement has been used by many practitioners to stabilize granular base, subbase, and subgrade materials (Berthelot and Gerbrandt 2002, Berthelot et al. 2007a, Berthelot et al. 2007b, Guthrie et al. 2007b, Kearney and Huffman 1999, Xu and Berthelot 2010). The benefits of cement stabilization are particularly recognized in cold regions where the addition of cement can improve the durability of frost-susceptible materials, such as granular materials (Berthelot and Gerbrandt 2002, Guthrie et al. 2007b, Miller et al. 2007). The amount of cement added to stabilize granular materials is important; too much cement will results in a stiff, brittle material and too little will result in no performance benefits (Berthelot et al. 2007b, Issa et al. 2001)

The addition of cement to stabilize RAP-base blended material retrieved from a full depth reclamation (FDR) project was investigated in the cold region of New England, USA (Miller et al. 2007). Samples were retrieved from the field and were mixed both on-site and in the laboratory with four percent cement. Samples were tested for durability and moisture susceptibility. It was found that cement stabilization reduced the dielectric values of the RAP-base blends, confirming previous published research (Guthrie et al. 2007b, Miller et al. 2007). Miller et al. (2007) advocates the use of cement as a stabilizer for RAP-base materials to improve the strength and durability of these materials, in addition to minimizing the frost and moisture susceptibility of these materials.

Based on modeling conducted by Thomas and May (2007), it was found that although emulsion stabilized RAP-base blended materials vary significantly with mix composition, binder type, and quantity of RAP, the addition of emulsion to stabilize RAP-base blended material in a FDR mix resulted in performance-related properties similar to asphalt concrete.

Cement-emulsion has been used for over 40 years to enhance the performance of asphalt surfaces (Issa et al. 2001). A study investigating the addition of cement and a high float emulsion to cold processed asphalt millings was conducted in Oklahoma (Issa et al. 2001). The purpose of this study was to investigate the characteristics of cement-emulsion stabilized asphalt millings for use as a cold-mix. Issa et al. (2001) found that other studies conducted on the addition of cement-emulsion to RAP in hot mix resulted in "substantial increases in strength, stability, and resistance to moisture." Issa et al. (2001) determined that a RAP mix with a high percentage of cement would be brittle and stiff. This study also found that more laboratory and field research needs to be conducted to examine the performance of cement-emulsion in RAP (Issa et al. 2001).

2.4 Benefits of Using RAP Systems

There is a significant amount of literature and research available detailing the benefits to using RAP materials in road rehabilitation. Overall, RAP can have the greatest economic, environmental, and engineering impact in pavement recycling (Emery 1993, Widyatmoko 2008). Research shows that the use of RAP materials in road construction reduce demands on depleting aggregate sources, divert significant amounts of RAP materials from landfills, reduce energy consumption, promote cost savings, and provide a means to recover, rejuvenate, and reuse the high-value binder and aggregate materials in RAP (Bennert et al. 2000, Emery 1993, Garg and Thompson 1996, Guthrie et al. 2007a, Horvath 2003, Taha et al. 2002, NCHRP 2008, Widyatmoko 2008).

Environmental awareness has increased pressure to design and construct new and innovative infrastructure that incorporates the three pillars of sustainable development: the economy, the environment, and social considerations (Emery 1993, Horvath 2003, Edil 2006, Duclos and MacKay 2009). Energy consumption is an environmental indicator that can be reduced by using RAP materials in road rehabilitation and construction (Horvath 2003). A study at the University of Saskatchewan (UofS) found that the use of recycled materials in road reconstruction reduced the overall energy consumption by more than 50 percent when compared to a conventional remove and replace (Haichert et al. 2009). As previously discussed, CIR and FDR provide environmental benefits in terms of reduced gas emissions and reduced fuel consumption.

There has been a steady increase in aggregate demand and consumption in the transportation section in recent years (Berthelot et al. 2010b, Berthelot et al. 2010d, Coulter 2003, Duclos and MacKay 2009, Marjerison 2000, Senior et al. 2008, MHI 2000). Likewise, the amount of RAP generated has increased given demands for infrastructure renewal. Near the City of Victoria, gravel pits have depleted while local demand for aggregates continues to increase. However, the City of Victoria estimates that seven percent of its total aggregate demand is met using recycled materials (Coulter 2003). The province of Ontario estimates 42 million tonnes of virgin aggregate were used for road construction between 2005 and 2008 (Duclos and MacKay 2009). During this time, 8.3 million tonnes of recycled material (approximately 19.8 percent of total road construction) was used in road construction (Duclos and MacKay 2009). By using stockpiled RAP material in place of quality granular materials, pressures on locating and transporting already depleting aggregate sources are eliminated and energy is conserved. MHI suggests the investigation of alternative road design and construction methods to reduce pressures on depleting aggregate sources (MHI 2000).

The use of RAP materials in road rehabilitation and construction also reduces pressures on landfill space. In some jurisdictions, recyclable materials such as RAP are banned from being disposed of in landfills (Duclos and MacKay 2009), eliminating disposal problem and preserves available landfill space (Edil 2006).

Annual transportation maintenance, rehabilitation, and new construction needs combined with limited budget funding enforce the economic advantages of using RAP materials in place of virgin aggregates. An increase of existing transportation design and construction costs combined with limited budget funding does not allow a jurisdiction to account for all its transportation infrastructure needs annually (COS 2008, Duclos and McKay 2009, Mirza 2007). As virgin aggregate sources become scarce, the cost to produce and haul aggregate will likely increase (Marjerison 2000, Horvath 2003). In urban centres, centrally located gravel pits are exhausted first, resulting in longer haul distances for urban centers. For example, the City of Saskatoon hauls virgin aggregate from up to 80 kilometers. Road recycling technologies can be of economic benefit in regions with depleting aggregate sources as recycling relies less on virgin aggregate (Marjerison 2000, MHI 2000).

Urban growth in combination with limited infrastructure budget funding, dwindling virgin aggregate sources, and increased conventional road materials and labour costs generate a need for more economically viable transportation infrastructure design and construction solutions. The economic benefit of using RAP materials in construction has been recognized in many Canadian and USA jurisdictions.

MHI has realized economic benefits to CIR and FDR construction processes for highway applications (Gerbrandt et al. 2000, Berthelot and Gerbrandt 2002). For example, MHI estimates that in a worse-case scenario, conventional road reconstruction can cost upwards of \$250,000/km; this is a significant cost considering CIR and FDR pilot projects in Saskatchewan have cost between \$80,000/km and \$130,000/km (Berthelot and Gerbrandt 2002). Berthelot and Gerbrandt (2002) further estimate that as conventional construction and material costs increase along with a rise in CIR and FDR projects, savings between CIR/FDR and conventional reconstruction could be as much as \$200,000/km. The FDR project constructed on Idylwyld Service Road in the City of Saskatoon saved approximately \$14.50/m^2 when compared to conventional reconstruction costs (Berthelot et al. 2009b). Savings were realized since full depth excavation was not required and construction time was significantly reduced when compared to conventional reconstruction.

Researchers in Illinois found that the use of RAP in pavement base and subbase layers was "economical and worthwhile" (Deniz et al. 2010). Bennert et al. (2000) reported that the using RAP in pavement layers was "a viable and cost-effective material for pavement designs". Edil (2006) investigated strategies for sustainable construction practices using recycled materials and found that overall "recycling will save millions of dollars annually to the industries in avoided landfill costs, [and will] generate cost-effective alternatives to traditional aggregates." A significant portion of these savings are achieved by reduced transportation energy (Horvath 2003, Haichert et al. 2009). RAP materials provide the cost-effective economic means to justify their use in road rehabilitation and construction (Emery 1993).

Hot and cold recycling technologies using RAP materials have been well developed in jurisdictions throughout USA and Canada. Performance monitoring of pavement systems constructed with RAP materials have proven to be structurally sound and to perform well in many cases (Berthelot and Gerbrandt 2002, Emery 1993, Duclos and MacKay 2009, Garg and Thompson 1996, Terrel et al. 1997). Guthrie et al. (2002, 2007) evaluated the use of RAP in aggregate blends and found that RAP increases moisture susceptibility in areas with poor drainage, high water tables, and with cold climatic effects. Many jurisdictions have had success with RAP systems and have found that, depending on the application, RAP systems can have material properties at least equivalent to virgin material counterparts (Garg and Thompson 1996, Widyatmoko 2008, Berthelot et al. 2009, Duclos and MacKay 2009, Jeon et al. 2009).

2.5 Limitations of Using RAP Systems

Although asphalt recycling is proven to be "technically sound and environmentally favorable and that it contributes to sustainable development" (Emery 1993), there are still transportation agencies that limit the amount of RAP used in transportation construction for reasons including lack of technical guidance, no specifications or protocols for implementation, and a lack of information regarding long-term performance of RAP materials (Coulter 2003, Edil 2006, Garg and Thompson 1996, NCHRP 2008). Despite the use of RAP materials in the USA and Canada, there is still limited technical guidance and information available with regards to RAP materials. Edil (2006) emphasizes that "researchers need to assure the technical information retrieved is disseminated to fellow engineers, technicians, and researchers."

A resistance to change within transportation agencies can limit the amount of recycling conducted in a jurisdiction. Although there has been increased awareness with regards to sustainability and asphalt recycling in the transportation sector, agency opposition still exists (Emery 1993). A poor past experience or a lack of experience with recycled materials can hinder RAP acceptance (Duclos and MacKay 2009, Taha et al. 2002).

Most transportation agencies in Canada have specifications for using RAP material in hot mix and cold in-place recycling (CIR), as previously discussed. However, specifications for other RAP systems, such as FDR and blended granular materials, are not as common (Coulter 2003, Duclos and MacKay 2009). For example, Ontario is the only jurisdiction in Canada that includes specification information with regards to the use of RAP in its granular base or subbase (MTO 2003). Using RAP can be limited due to a lack of laboratory testing and field performance data (Garg and Thompson 1996, Taha et al. 2002). Even in jurisdictions where the use of RAP is approved and specifications do exist, Duclos and MacKay (2009) found that "many agencies and consultants continue to prohibit the use of granular materials incorporating these 'approved' recycled materials, largely due to lack of experience or an unfavorable past experience."

Much of the literature available focuses on both locally available RAP materials dependent on jurisdiction and laboratory characterization that often includes variations of conventional laboratory characterization tests (Horvath 2003, Taha et al. 1999). There are concerns with using conventional laboratory tests designed to characterize unbound aggregates for RAP materials (Berthelot et al. 2009a, Edil 2006). More laboratory testing and research is needed, in addition to the construction of field test sections to validate laboratory findings, to validate performance-prediction accuracy of laboratory tests, and to monitor the adequacy of recycled materials by jurisdiction (Horvath 2003, NCHRP 2008, Widyatmoko 2008).

Using RAP systems in road construction is limited by a lack of performance indicators that characterize the material. In some jurisdictions, for projects that implement the use of RAP in road construction, quality control and quality assurance requirements cannot be met due to a lack of compatibility between conventional road building materials and recycled materials in terms of performance testing, laboratory characterization, and design. In these cases, agencies often adopt special provisions for contracts using RAP materials to reflect the past performance (Duclos and MacKay 2009).

In some jurisdictions, RAP systems do not perform as well as expected in the field and are excluded from use in future road construction (Duclos and MacKay 2009, Senior et al. 2008). This is often due to concerns with regards to the technical properties and durability of RAP systems.

RAP materials that are stockpiled for future use are often comprised of variable sized pieces including large slabs of asphalt pavement, granular materials, fines, or deleterious material. These stockpiles are often made up of RAP generated from various locations which can influence the composition of the end-product. Depending on the size of the stockpiled material, RAP can be further processed, crushed, and screened for further use in hot and cold recycling processes. Use of RAP materials can be limited by the methods used for processing and crushing the material (Robinson et al. 2004).

2.6 Crushing RAP Materials

Crushing and processing RAP materials is not well documented. Many researchers discuss the importance of ensuring that RAP materials are processed adequately to achieve material properties equivalent to those necessary for the application of virgin granular base materials or virgin HMAC materials (Deniz et al. 2010, Garg and Thompson 1996, MacGregor et al. 1999, NCHRP 2008, Robinson et al. 2004, Senior et al. 2008). A majority of the research conducted with regards to using RAP as a granular base material focuses on the use of RAP in blended granular base or subbase materials where the RAP material is either retrieved during the full depth reclamation (FDR) process or taken from local RAP stockpiles, where there can be significant variations in the size of the RAP (Berthelot et al. 2009a, Berthelot et al. 2010b, Berthelot et al. 2010e, Coulter 2003, Robinson et al. 2004). This RAP material may be processed and crushed further.

Conventional aggregate crushing operations typically employ jaw and cone type crushing designed for pit run aggregate deposits. However, when employed for crushing RAP rubble materials, conventional crushing methods can reduce the processing efficiency as well as the quality of the final crushed RAP product (Berthelot et al. 2009a, Berthelot et al. 2010b).

In 2008, the City of Saskatoon commissioned impact crushing equipment specifically designed to crush RAP materials and capable of generating multiple sized materials at once. The crushing process for manufacturing the crushed RAP rubble materials included stockpiling the RAP rubble material, processing the rubble material by breaking up the large slabs of asphalt pavement (as illustrated in Figure 2.2), and crushing the RAP rubble material (as illustrated in Figure 2.3). Figure 2.3 illustrates the impact crusher. The impact crusher uses integrated screens to produce multiple RAP materials at once.

Figure 2.2 Processing RAP Rubble Materials in City of Saskatoon (photo courtesy of PSI Technologies Inc.)

The impact crusher was found to reduce the technological limitations of conventional crushing equipment and improve the gradation of the crushed RAP rubble material. Crushing RAP using an impact crusher improves the reduction ratio of the RAP and creates angular, cubical particles that were not stripped of asphalt cement (Berthelot et al. 2009a, Berthelot et al. 2010b, Garg and Thompson 1996).

Figure 2.3 Impact Crusher Generating Crushed RAP Rubble Materials in City of Saskatoon (photo courtesy of PSI Technologies Inc.)

The gradation of crushed RAP indicates field performance (Garg and Thompson 1996). Aggregate angularity and fine sand content are of particular concern when processing and crushing RAP materials. Aggregate angularity influences the number of fractured faces of aggregate particles and particle interlock during compaction. Processing and crushing RAP aggregates can increase the number of fractured faces on a RAP particle (Berthelot et al. 2009a, Berthelot et al. 2010b, Garg and Thompson 1996).

The uniformity of a RAP gradation is important to minimize fines content and to minimize variations in RAP material retrieved from different sources (Garg and Thompson 1996, Guthrie et al. 2007a, MacGregor et al. 1999, NCHRP 2008, Robinson et al. 2004, Senior et al. 2008). This is significant for stockpiled RAP material, which often consists of RAP materials retrieved from various sources and by different methods. The National Cooperative Highways Research Program (NCHRP) reported that the “quantity and nature of fines fraction directly influence[s] moisture sensitivity” of RAP materials (2008). NCHRP (2008) determined that a minimal amount of fines are produced during RAP processing and crushing. This is consistent with findings by other researchers (Berthelot et al. 2009a, Berthelot et al. 2010b, Deniz et al. 2010, Garg and Thompson 1996, MacGregor et al. 1999, Robinson et al. 2004, Senior et al. 2008). Processing, crushing, and screening RAP materials is important to the performance quality of RAP systems.

2.7 City of Saskatoon Transportation Infrastructure Challenges

As discussed in Chapter One, the City of Saskatoon is faced with challenges related to its transportation infrastructure, as summarized below.

- There is an increased demand for new transportation infrastructure construction and the rehabilitation of ageing transportation infrastructure.
- Material and labour costs are rising.
- There are few virgin aggregate sources in close proximity to the COS.
- Transportation infrastructure renewal has led to an increase in stockpiled RAP materials.

Further to these challenges include the implementation of mechanistic-empirical design guides by transportation regulatory agencies such as AASHTO and the Transportation Association of Canada (TAC), changing field state conditions, and the City of Saskatoon's annual budget. The City of Saskatoon is faced with challenges of managing diverse and ageing road infrastructure assets. Determining optimal rehabilitation solutions for in-service road structures in varied condition states under wide ranging field state conditions is of primary concern. Given the present day challenges of structurally upgrading in-service road infrastructure assets in diverse field state conditions, there is a need to incorporate new innovative materials, changing field state conditions, and mechanistic design methods in road rehabilitation decision making.

2.7.1 Implementation of Mechanistic-Empirical Design Guide

As discussed at the beginning of Chapter Two, the MEPDG provides benefits over traditional empirical design methods. Overall, the MEPDG is capable of accounting for traffic loadings, climate, materials used in road construction, and design life to reduce overall lifecycle costs and to improve structural performance (AASHTO 2002). Implementation of the MEPDG is underway in some USA and Canadian jurisdictions.

The City of Saskatoon presently designs and rehabilitates roads using primarily empirical methods. For example, the COS base aggregate specification specifies traditional empirical tests such as California bearing ratio (CBR) testing (COS 2005).

The COS employs structural asset management to determine the structural capacity of its in-service roads (Prang and Berthelot 2009). Using pavement distress data and heavy weight deflectometer (HWD) data, the COS is capable of determining the condition state category of its roads. The condition states determine the rehabilitation required to restore the segment to a "good" condition state. Many agencies are moving towards structural asset management valuation systems which provide actual performance data and account for capital assets and costs associated with its infrastructure. HWD deflection measurements can be used in mechanistic modeling to determine the behaviour of the pavement structure.

2.7.2 Changing Field State Conditions

Pavement deterioration and ageing of City of Saskatoon roads is due to increasing traffic loadings, variable climatic conditions, and changing environmental conditions. Traffic loadings within the City of Saskatoon have increased as a result of greater truck weights and dimensions, more public transportation buses, and accelerated pavement deterioration. Urban roadways are more sensitive to heavy traffic loadings when compared to rural roads (Thomas 2008).

Climatic effects, including moisture and freeze-thaw conditions, have a significant impact on the performance of a pavement structure, particularly aged pavement structures. For example, pavement structures weaken during the spring thaw period (Berthelot et al. 2008a). Saskatchewan is a jurisdiction that is subject to temperature extremes with regards to weather resulting in pavements rutting in hot temperatures and severe thermal cracking in cold temperatures.

Changing environmental conditions have been observed as the City of Saskatoon expands. For example, southern expansion of the city limits has resulted in new home and road construction in sandy subgrade areas (Prang 2010). Eastern expansion of the city limits has resulted in new home and road construction in areas with a rising water table and expansive clay subgrades (Prang 2010). These changing environmental conditions were not accounted for in initial pavement design; ten years later, these roads are structurally failing due to excess moisture, poor drainage, and pavement deterioration (Prang and Berthelot 2009).

2.7.3 Costs and Budget

The City of Saskatoon deals with rising capital costs and ageing infrastructure that are not always reflected in its annual budget. In 2007, the City of Saskatoon City Council Capital Budget struggled with "funding shortfalls related to infrastructure deficiencies" (COS 2007). In recent years, the City of Saskatoon has prioritized new transportation infrastructure projects that require a significant amount of financial resources in its annual budget in addition to focusing significant budget amounts to residential and commercial land development (COS 2007, COS 2008, COS 2009, COS 2010). These financial budgetary allocations for new transportation infrastructure projects and new developments reflect the City's continued and steady population growth (COS 2008, COS 2010); however, the transportation infrastructure deficit remains minimally addressed. In 2007 and 2008, for example, the City of Saskatoon (2007, 2008) allotted \$3.7 million and \$4.0 million for maintenance and replacement of local, collector, and arterial roads. This is insignificant when considering that in 2008 almost 40 percent of the total annual COS Capital Budget of \$218,386,000 was allocated to land development (COS 2008). Although this does reflect the recent significant growth in the City of Saskatoon, it also confirms the findings in Mirza's report addressing Canada's infrastructure deficit (2007) that "significant funding gaps exist for repair and rehabilitation of current assets" and there is a "pressing need to build new infrastructure" (Mirza 2007).

2.8 Chapter Summary

This chapter presented the history and background of recycling reclaimed asphalt pavement (RAP) in road construction, including benefits and limitations of using RAP. This chapter also presented information on City of Saskatoon transportation infrastructure and materials.

Benefits to using RAP materials in road construction include reduced demands on depleting aggregate sources, diverting significant amounts of RAP materials from landfills, reduced energy consumption, promoting cost savings, and providing a means to recover and reuse the high-value binder and aggregate materials in RAP.

RAP is not typically used in a base layer comprised of 100 percent RAP material. There are no specifications for using RAP materials in a base layer comprised of 100 percent RAP material. This is due to limited technical guidance for transportation agencies, no specifications or protocols for implementing RAP materials, and a lack of information regarding long-term performance of RAP materials.

Processing, crushing, and screening RAP materials is important to the performance quality of RAP systems. The uniformity of a RAP gradation is important to minimize fines content and to minimize variations in RAP material retrieved from different sources. An impact crusher improves the gradation of crushed RAP rubble material and results in more angular, cubical particles that are not stripped of asphalt cement.

CHAPTER 3 EXPERIMENTAL PROGRAM

This research focuses on the laboratory characterization of reclaimed asphalt pavement (RAP) base layers made of 100 percent crushed RAP rubble material. This chapter reports various materials testing and laboratory performance research related to the use of RAP materials in pavement base layers. This chapter also presents details of the experimental program used in this research. Details of materials and testing procedures used in this research are provided.

3.1 Laboratory Characterization Background

There are limitations of using conventional laboratory tests designed to characterize unbound aggregates to determine the performance of RAP materials (Edil 2006, Saeed 2008). RAP materials are composed of aggregates and asphalt concrete binder and may not be considered strictly 'unbound materials', as virgin aggregates are defined. Furthermore, many conventional laboratory tests are empirically based and not designed for recycled materials such as RAP. Since there are no standard specifications, testing protocols, or performance indications for RAP materials, variability in laboratory test protocols used for recycled materials exists.

The NCHRP Report 598 provides recommendations for performance-related procedures to evaluate the performance of recycled materials, including RAP and Portland cement concrete (PCC), for use in unbound pavement layers (Saeed 2008). The research conducted as part of NCHRP Report 598 included evaluating the applicability of conventional aggregate tests for recycled materials and developing or modifying tests if required. RAP materials from difference sources were blended with virgin granular materials and a range of tests were carried out. Despite an observation that "constructability concerns raise questions about the validity of the test intended for evaluating virgin aggregate for use in evaluating RAP" materials, Saeed (2008) concluded that the performance of recycled aggregates in unbound pavement layers relied on gradation, moisture-density relationship, Micro-Deval for toughness, resilient modulus for stiffness, static triaxial and repeated load for shear strength (optimum moisture content and saturated condition), and the tube suction test for frost susceptibility. Although a range of test parameters were recommended for the use of RAP in blends with virgin aggregates in different climatic conditions and traffic levels, the NCHRP Report 598 outlined the following recommendations for further research: modifications to the repeated load and moisture content tests; confirmation of the validity of the recommended tests under a range of service conditions; and field validation.

In a more recent review of laboratory tests used to evaluate the performance of RAP materials blended with virgin aggregates in unbound pavement layers by Edil and Schaertl (2010), the most common tests used to determine strength parameters, stiffness, permanent deflection, moisture susceptibility, and to assess the durability of the RAP materials were summarized. This summary of laboratory tests used to evaluate the performance of RAP materials in unbound pavement layers differs from the test recommended in NCHRP Report 598, further emphasizing the variability in laboratory tests used for recycled materials.

The following sections summarize laboratory tests and methods (as listed below) used for evaluating the performance of RAP materials in unbound aggregate layers, as detailed in the literature. Laboratory test limitations and ability to adequately represent performance in the field are discussed.

- Aggregate gradation test, ASTM C117 and C136
- Proctor compaction method, ASTM D698 or ASTM D1557
- Gyratory compaction method
- California bearing ratio (CBR) test, ASTM D1883
- Resilient modulus and permanent deformation test, NCHRP 1-28A
- Tube suction test (TST)
- Vacuum saturation test
- Triaxial frequency sweep test (RaTT)

3.1.1 Aggregate Gradation Test

Aggregate gradation is determined by sieve analysis, in accordance with the American Society for Testing and Materials (ASTM) C117 and C136. Aggregate gradation measures the particle size distribution of the material and can be used to classify the aggregates (ASTM 2004, ASTM 2006a, Saeed 2008). Aggregate base gradations may be described as well graded, poorly graded or gap-graded (Craig 1997, Roberts et al. 1991). A well graded aggregate (also called dense graded) gradation has evenly distributed particles and is represented by a smooth particle-size distribution curve. Poorly graded aggregates have a high amount of particles in one size. Gap-graded aggregates have particles in the larger size and smaller size, but lack particles in the mid-range of size.

Gradation and aggregate angularity influence the mechanical properties of a pavement layer and field performance. Gradation influences the moisture and frost susceptibility, durability, and stiffness of an unbound aggregate layer (ASTM 2004, ASTM 2006a, Guthrie et al. 2007b, Roberts et al. 1991, Saeed 2008). Aggregate angularity influences the structural stiffness of an unbound aggregate layer (Roberts et al. 1991).

Aggregate angularity refers to the shape and number of fractured faces of the aggregate particles and influences particle interlock during compaction (Roberts et al. 1991, Saeed 2008). COS defines coarse aggregate as the material retained on the 5 mm sieve (2005). This differs from ASTM due to the metric conversion; ASTM (2004, 2006a) defines coarse aggregate as the material retained on the No. 4 (4.75 mm) sieve.

ASTM defines fines content as the material passing the No. 200 (75 µm) sieve. COS uses a metric sieve set that defines fines content as the material passing the 71 µm sieve (2005). Fines and fine sand particles influence the mechanical properties and moisture sensitivity of a granular material (Berthelot et al. 2009a, Berthelot et al. 2009b, Saeed 2008). This is particularly the case in Saskatchewan field state conditions (Berthelot et al. 2009a, Berthelot et al. 2009b). A low amount of fines will ensure adequate drainage and permeability (Senior et al. 2008).

Deleterious material, including clay particles, wood particles, and organic content, affect the performance of the aggregate system. Agencies typically specify a maximum amount of organic content permissible, by weight, in the aggregate gradation to ensure their performance (COS 2005).

For unbound aggregate materials, the COS specifies gradation specifications for subbase aggregate, base aggregate, asphalt aggregate, street sanding aggregate, concrete aggregate, plaster sand, pipe bedding aggregate, and drainage rock (COS 2005). Gradation specification limits differ depending on the use of the material. For example, the crushed drainage rock has a top size of 25 mm and permits more open graded aggregates. The subbase aggregate gradation also has a top size of 25 mm but permits a larger bandwidth of fines content compared to the crushed rock and the base aggregate specifications.

COS base aggregate specification limits are listed in Table 3.1 and illustrated in Figure 3.1 (COS 2005). The base aggregate specification limits have a top size of 18 mm and a fines content bandwidth of six to eleven percent. With regards to coarse aggregate angularity, the COS base aggregate specifications require at least 50 percent of the material (by weight) retained on the 5 mm sieve to have one or more fractured faces (COS 2005). The COS base aggregate specification also indicates that the less than three percent organic content of the material can pass the 5 mm sieve (COS 2005).

Table 3.1 COS Base Aggregate Gradation Specification (COS 2005)

Sieve Designation	Percent by Weight Passing
25 mm	100
18 mm	87-100
12.5 mm	72-93
5 mm	45-77
2 mm	29-56
900 µm	18-39
400 µm	13-26
160 µm	7-16
71 µm	6-11

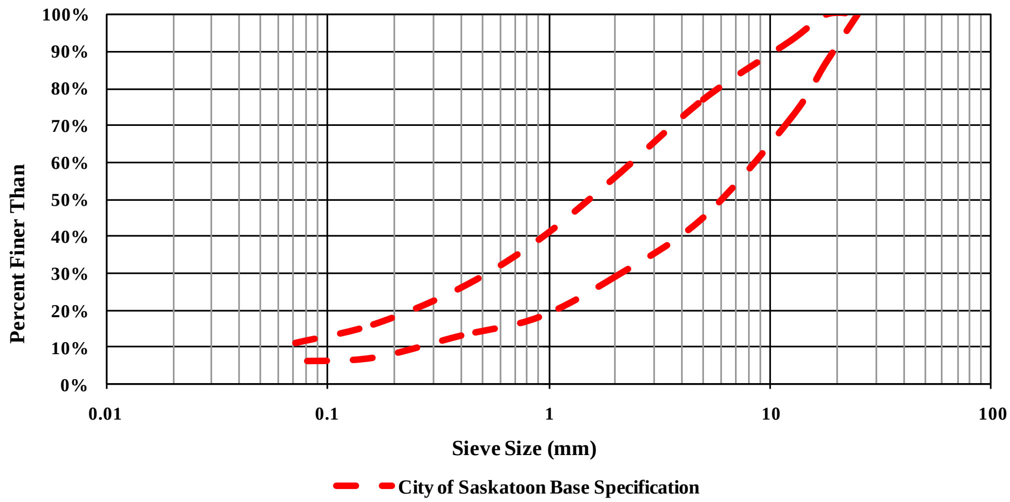


Figure 3.1 COS Base Aggregate Gradation Specification (2005)

3.1.2 Proctor Compaction Method

Proctor laboratory compaction is used to determine the maximum dry density and optimum water content of an unbound material. Proctor laboratory compaction is conducted in accordance with ASTM D698 or ASTM D1557 (ASTM 2007a, 2009a). ASTM D698 refers to the standard Proctor compaction test and ASTM D1557 refers to the modified Proctor compaction test. Both tests use an impact hammer of specific effort to compact an aggregate sample in a cylindrical mold. The main difference between the compaction tests is that the modified Proctor compaction test is conducted with increased effort of 2,700 kN-m/m^3 compared to the standard Proctor effort of 600 kN-m/m^3 (ASTM 2007a, 2009a). Both "laboratory compaction tests provide the basis for determining the percent compaction and molding water content needed to achieve the required engineering properties" (ASTM 2007a, 2009b). Adequate compaction results in satisfactory material density, shear strength, stiffness, and permeability. Figure 3.2 illustrates Proctor compaction laboratory equipment.

Some researchers have used the modified Proctor to compact laboratory specimens containing RAP material and have not identified any deficiencies with the impact compaction method (Blankenagel and Guthrie 2006, Guthrie et al. 2007a, Guthrie et al. 2007b, Jeon et al. 2009, Saeed 2008). However, issues with Proctor compaction have been identified by researchers investigating the performance of RAP-granular blended samples (Berthelot et al. 2009a, Berthelot et al 2010d, Deniz et al. 2010, Kim et al. 2007, Kim et al. 2009, Taha et al. 1999, Taha et al. 2002). For example, increased amounts of RAP blended with granular materials did not compact well or remain intact in the Proctor compaction mold. Ease of Proctor compaction increases with a decrease in RAP materials. It is hypothesized that RAP materials are sensitive to Proctor compaction as they contain bound particles (Berthelot et al. 2009a, Berthelot et al 2010d, Deniz et al. 2010, Kim et al. 2007, Kim et al. 2009, Taha et al. 1999).

Taha et al. (1999) used the modified Proctor method to compact RAP-granular aggregate blended samples. During compaction of all RAP-granular aggregate blends, it was observed that larger RAP particles were breaking down. During compaction of samples containing a higher RAP content, the samples with low moisture contents fell apart and did not stay intact when the mold was removed; samples with high moisture contents had water draining out of the mold. The sample containing 100 percent RAP did not achieve proper compaction using the impact compaction method of Proctor compaction (Taha et al. 1999). The 100 percent RAP sample had a maximum dry density of approximately 83 percent of the 100 percent virgin aggregate samples maximum dry density, indicating the 100 percent RAP sample does not compact well when compacted using impact compaction (Taha et al. 1999).

Deniz et al. (2010) used an effort between the standard Proctor effort and the modified Proctor effort to compact varying types of RAP aggregates. The RAP materials were found to have lower densities than the virgin materials, due to inadequate compaction. Garg and Thompson (1996) found Proctor compacted RAP densities were low compared to virgin aggregate base densities and attributed this to “the more open-graded nature of RAP.” Senior et al. (2008) attribute lower densities of RAP blended aggregate samples to “the coarser aggregate grading and the presence of RAP particles in the mix” during impact compaction.

Some literature details problems arising with Proctor compaction of RAP materials and RAP blended materials may be attributed to the bound aggregate attributes of the RAP material (Berthelot et al. 2009a, Berthelot et al 2010d, Deniz et al. 2010 Kim et al. 2007, Kim et al. 2009, Taha et al. 1999). RAP material includes both granular aggregates and granular aggregates coated in asphalt cement; by nature, RAP material is a bound material. The Proctor compaction test is designed for unbound aggregates (ASTM 2007a, 2009a).

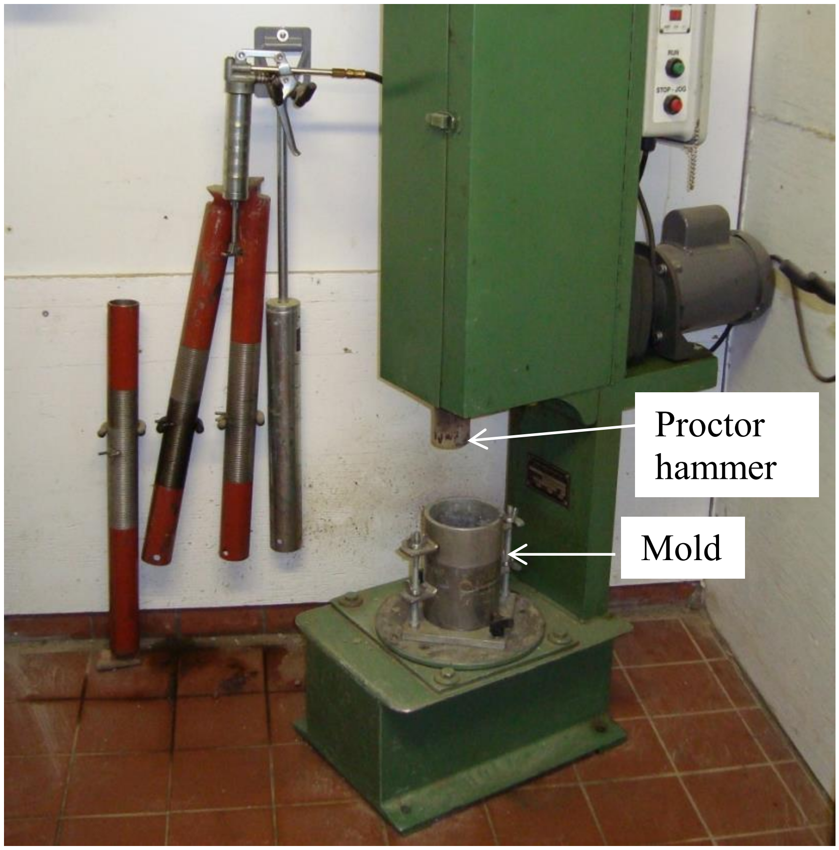


Figure 3.2 Proctor Compaction Laboratory Equipment

Proctor compaction has been questioned with regards to how closely it replicates field compaction. Studies conducted by Kim et al. (2007, 2009) compared Proctor compaction maximum dry densities and optimum moisture contents of virgin aggregate samples to those retrieved from the field. The values of maximum dry density and optimum moisture content achieved by Proctor compaction were not representative of field compaction. Proctor compaction did not provide adequate density of the virgin granular material and compaction was deemed incomplete (Kim et al. 2007). The same results were found for RAP-aggregate blended samples (Kim et al. 2009).

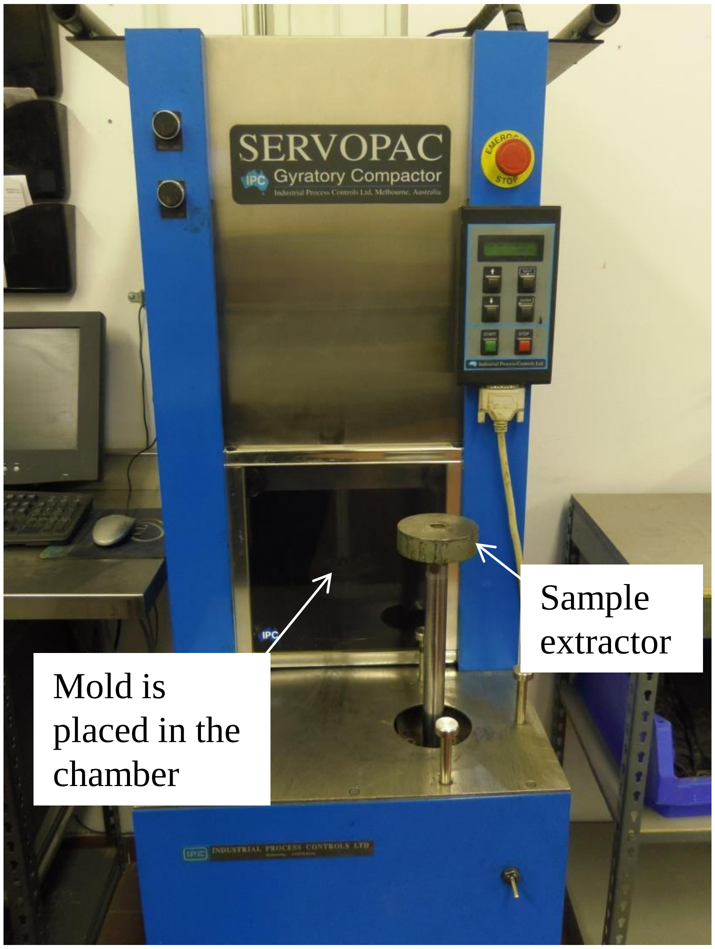
3.1.3 Gyratory Compaction Method

The gyratory compaction method provides an alternative to the standard Proctor compaction method. The gyratory compaction method is more representative of field measured compaction (Kim et al. 2007, Kim et al. 2009, Sukumaran et al. 2010). Gyratory compaction has been used to compact both bound and unbound pavement materials (Asphalt Institute 2001, Anthony 2008, Gould et al. 2003, Kim et al. 2007, Kim et al. 2009, Salifu 2010, Sukumaran et al. 2010). Gyratory compaction is conducted in accordance with ASTM D6925 or ASTM D7229 for hot mix asphalt and cold mix asphalt, respectively (ASTM 2009b, 2008). The AASHTO standard for the gyratory compactor is AASHTO TP-4.

Gyratory compaction was first known as Superpave™ gyratory compaction (SGC) and was developed by the Strategic Highway Research Program (SHRP) for the Superpave™ (SUperior PERforming Asphalt PAVEments) asphalt mix design system (Asphalt Institute 2001, Gould et al. 2003). The purpose of developing the SGC was to employ realistic compaction of specimens to densities actually achieved in the field (Asphalt Institute 2001). Figure 3.3 illustrates SGC equipment, including the sample molds and the compaction equipment.

The SGC employs a cylindrical mold of 150 mm in diameter. The specimen is placed in the mold and a vertical pressure of 600 kPa is applied to the specimen while the mold rotates at an angle of 1.25 degrees. The SGC is computer-controlled and monitors the increase in specimen density. When the optimum density is achieved, the compactor will stop. The Superpave™ gyratory compactor is capable of compacting granular specimens, hot mix specimens, or specimens composed of recycled material (Gould et al. 2003, Kim et al. 2007, Kim et al. 2009, Berthelot et al. 2009a).

a) Sample Mold



b) Compaction Equipment

Figure 3.3 Gyratory Compactor Laboratory Equipment

3.1.4 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) test is an empirical strength test that compares the strength of an unbound material to crushed limestone. It is outlined in ASTM D1883 (2007b). The CBR test was developed as part of the American Association of State Highway Official (AASHO) Road Test in California, USA (AASHTO 1986). Despite its empirical limitations, the CBR test is a well-known and well used test employed for pavement design in Canada and USA. This method of pavement design is dependent on the subgrade type and the materials used to construct the pavement structure, which are specifically related to the CBR values. CBR samples are Proctor compacted by impact compaction and may be tested in a soaked or unsoaked condition (ASTM 2007b).

Although the CBR test is limited to unbound aggregates and an empirical relationship to crushed limestone, it is a widely used test in pavement design. For example, MHI and COS employ the CBR Shell Design Curves for pavement structure design (COS 2008a, Thomas 2008). COS specifies a minimum CBR of 65 in the unsoaked condition for base aggregate compacted to 100 percent of the maximum density, determined by standard Proctor compaction (COS 2005). Based on the limitations of the CBR test and the limitations of the Proctor compaction test (as previously summarized), these test methods are not suitable for RAP materials as they were developed and designed for unbound materials such as granular base, subbase, and subgrade materials.

Proctor compaction and CBR testing have been used to evaluate the material properties of RAP blended granular materials. Various studies indicate CBR testing results of RAP-aggregate blended samples decrease with increasing RAP contents (Guthrie et al. 2007, Senior et al. 2008, Taha et al. 1999, Taha et al. 2002). Similarly, the density of the samples decreased as RAP content increased. Considering samples with an increased amount of RAP (including 100 percent RAP) do not achieve proper compaction using Proctor compaction, it is reasonable to assume the CBR values would be low.

3.1.5 Resilient Modulus and Permanent Deformation Test

The resilient modulus and permanent deformation test is typically performed in accordance with protocols outlined in NCHRP 1-28A for both unbound materials and hot mix asphalt materials. Material specimens are tested under stress states, moisture conditions, and densities representative of those in a pavement layer under moving wheel loads (Abushoglin and Khogali 2006). The resilient modulus and permanent deformation test is conducted by maintaining a constant confining pressure in a typical triaxial cell while applying repeat axial loads to a cylindrical, compacted specimen. The specimen is compacted by gyratory compaction or vibratory hammer compaction. Material properties generated from this test provide information on the performance of materials under field-state conditions and are used in mechanistic-empirical pavement design guides (NCHRP 2004, Abushoglin and Khogali 2006).

Figure 3.4 illustrates a schematic of the triaxial test chamber for resilient modulus and permanent deformation test of granular material (Abushoglin and Khogali 2006). The cylindrical test specimen is compacted in a rubber mold and placed in the triaxial test chamber. The loading ram applies an axial repetitive deviator stress (s_d) at various load and cycle durations. A supply of air to the triaxial chamber applies the confining pressure. A repetitive load level is selected from the test software and the test is carried out. Two linear variable differential transformers (LVDTs) are used to measure the axial deformation of the specimen. A haversine wave of load duration is used for testing granular materials (Abushoglin and Khogali 2006).

The protocol outlined in NCHRP 1-28A and variations of this protocol are used determine the resilient modulus and permanent deformation of a material. Resilient modulus (M_R) is an elastic modulus and is a measure of a material's stiffness under repeated loads. Permanent deformation is determined using the permanent strain generated by each cycle of the test. Resilient modulus is defined as the ratio of the repeated deviator stress to the peak recoverable axial strain:

$$\boldsymbol{M_R = {}^{\sigma_d}/_{\varepsilon_r}} \qquad \textbf{(3.1)}$$

where:

M_R = Resilient Modulus (MPa),

σ_d = Repeated deviator stress (MPa), and

ε_r = Peak recoverable axial strain.

The protocol outlined in NCHRP 1-28A and variations of this protocol are used determine the resilient modulus and permanent deformation of a material. Resilient modulus (M_R) is an elastic modulus and is a measure of a material's stiffness under repeated loads. Permanent deformation is determined using the permanent strain generated by each cycle of the test. Resilient modulus is defined as the ratio of the repeated deviator stress to the peak recoverable axial strain:

Resilient modulus stiffness of the base layer indicates its load carrying capacity; permanent deformation resistance of the base layer indicates its resistance to rutting. These are two important material properties of an unbound base layer (Jeon et al. 2009). Use of the resilient modulus and permanent deformation test has increased as the pavement design industry moves towards mechanistic-empirical pavement design that relies less on empiricism and static tests and more on mechanistic tests that provide indicators of a material's realistic field performance (NCHRP 2004, Abushoglin and Khogali 2006, Jeon et al. 2009, Kim et al. 2009).

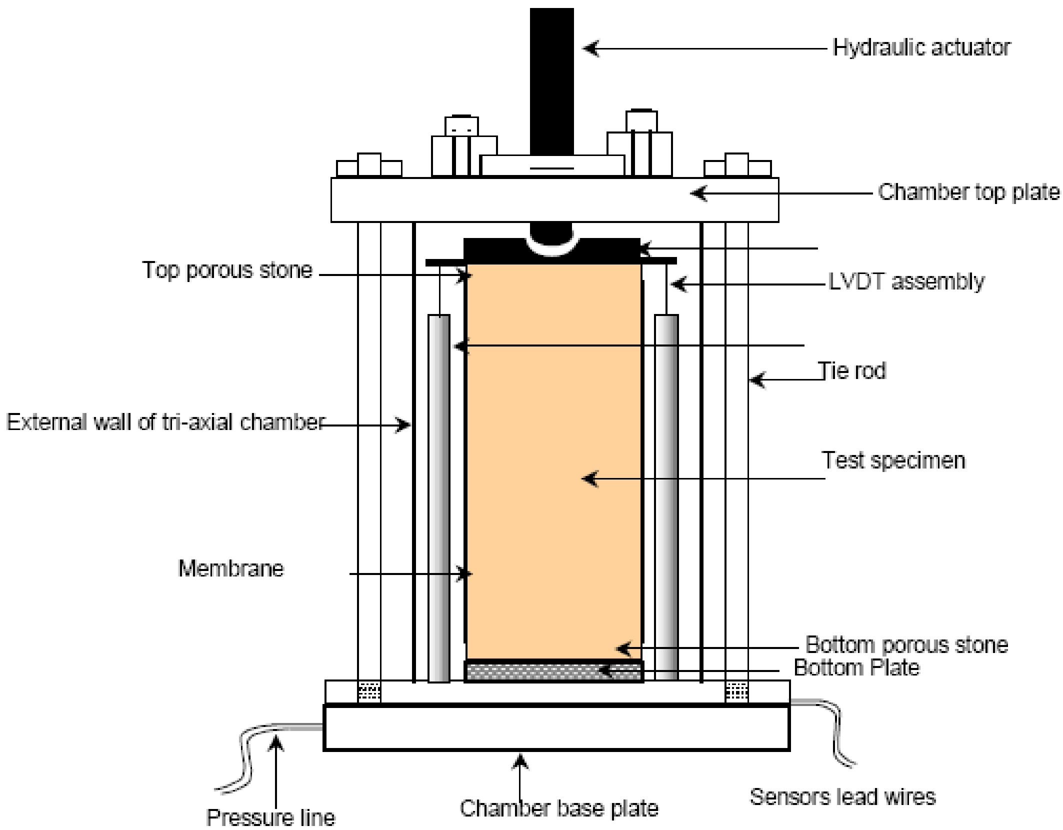


Figure 3.4 Schematic of the Triaxial Test Chamber for Resilient Modulus and Permanent Deformation Test of Granular Material (Abushoglin and Khogali 2006)

RAP materials blended with virgin aggregate have been subjected to resilient modulus and permanent deformation testing to evaluate predicted field performance. Samples of 100 percent RAP materials from various jurisdictions had resilient modulus values comparable to or greater than samples of virgin aggregates (Bennert et al. 2000, Garg and Thompson 1996, Jeon et al. 2009, Kim et al. 2007, Kim et al. 2009). Kim et al. (2007) of Minnesota found resilient modulus values indicated RAP samples were stiffer at a higher confining pressure. At a low confining pressure, 50/50 blends of RAP/virgin aggregate were found to have the same stiffness (Kim et al. 2007). Bennert et al. (2000) observed a general increase in resilient modulus with an increase in RAP content.

The permanent deformation results of RAP materials blended with virgin aggregates were also similar across various jurisdictions. RAP samples were more susceptible to permanent deformation than virgin aggregate samples (Bennert et al. 2000, Garg and Thompson 1996, Jeon et al. 2009, Kim et al. 2007, Kim et al. 2009). Bennert et al. (2000) observed a general increase in permanent deformation with an increase in RAP content.

Jeon et al. (2009) found that RAP materials had better resistance to permanent deformation at high stress levels; and at low stress levels, the RAP materials had poor resistance to permanent deformation. Vibratory hammer compaction method was used in Jeon et al.'s (2009) study and might not have resulted in complete compaction of the RAP-virgin aggregate blended materials. Poor resistance to permanent deformation at low stress levels was attributed to two reasons: firstly, during the initial load cycles of the test at a low stress level, further compaction occurs and may result in permanent deformation; secondly, the RAP material could further break down under initial loading, causing permanent deformation (Jeon et al. 2009).

The compaction method used to prepare specimens for resilient modulus and permanent deformation testing can affect the results of the test. Although NCHRP 1-28A requires gyratory compaction of specimen, variations of this protocol use vibratory hammer compaction. Kim et al. (2007) uses gyratory compaction instead of vibratory hammer because "the density of a gyratory-compacted specimen [is] closer to the field density." That study found that although RAP samples were more susceptible to permanent deformation than virgin aggregate samples, 100 percent RAP samples had resilient modulus values comparable to or greater than samples of virgin aggregates.

3.1.6 Tube Suction Test (TST)

The tube suction test (TST) was developed by the Finnish National Road Administration and the Texas Transportation Institute. The TST assesses the moisture susceptibility of aggregate materials by monitoring the capillary rise of moisture in a compacted sample by measuring its surface dielectric value (Guthrie et al. 2002, Scullion and Saarenketo 1997). Dielectric values indicate the moisture susceptibility and expected performance of the aggregate material. Comparisons to field measured dielectric values indicate the TST is accurate in measuring moisture susceptibility (Berthelot et al. 2008a, Miller et al. 2007, Scullion and Saarenketo 1997, Syed et al. 2000).

There is no standard test procedure for the TST, but the methodology is well documented. Scullion and Saarenketo (1997) provide a detailed methodology of the TST. To facilitate the tube suction test, samples are compacted, cured, dried, and placed in a water bath. The surface dielectric value is measured daily using an Adek Percometer™. The Adek Percometer™ is illustrated in Figure 3.5. Dielectric values are interpreted using empirical correlations with aggregate base materials. For example, the typical dielectric values of asphalt and aggregate base material are two and six to 20, respectively (Scullion and Saarenketo 1997).

The TST has been used to evaluate the moisture susceptibility of RAP materials. Guthrie et al. (2007a, 2007b) has used the TST to determine the moisture susceptibility of RAP-aggregate blended samples. Samples with 25 percent RAP had increased dielectric values when compared to virgin aggregate samples. As RAP was increased to 100 percent, the dielectric values steadily decreased, indicating the RAP material increased moisture susceptibility.

Figure 3.5 Adek Percometer™ used for Tube Suction Test (www.roadscanners.com/en/hardware/index.html)

3.1.7 Vacuum Saturation Test

Variations of vacuum saturation tests have been used to assess the moisture susceptibility of road materials (BBA 2008, Berthelot et al. 2010c, Birgisson et al. 2004, Huang et al. 2005, Kringos et al. 2009). Vacuum saturation typically involves a cored or compacted material samples to be subjected to full submersion in water, put under vacuum, and allowed to fully saturate prior to draining. After draining, the sample is typically tested for stiffness. Vacuum saturation provides a laboratory means of subjecting road materials to severe moisture conditioning in an effort to assess their performance.

A procedure following AASHTO T-283 was used by Birgisson et al. (2004) and Kringos et al. (2009) to assess the moisture susceptibility of hot mix asphalt gyratory compacted samples. The samples were placed in a water bath at a temperature of 60ºC for 24 hours, and then allowed to drain for 36 hours prior to undergoing further testing. Vacuum saturation levels were found to be between 65 and 80 percent (Birgisson et al. 2004, Kringos et al. 2009). A similar procedure is implemented in Wyoming Department of Transportation (WYDOT) to assess moisture susceptibility (Huang et al. 2005). Variations of this test method exist to assess the freeze-thaw susceptibility of materials.

A vacuum saturation process was used by Berthelot et al. (2010d) to assess the moisture susceptibility of gyratory compacted lime-treated hot mix asphalt specimens. The purpose of vacuum saturation was to imitate high moisture conditions (Berthelot et al. 2010c). Samples were first vacuum saturated in a room temperature water bath chamber for eight hours, drained for 16 hours, then tested in a rapid triaxial test apparatus to assess mechanical properties. To assess the freeze-thaw effects, the samples were vacuum saturated for eight hours in a room temperature water chamber, and then frozen at minus 15ºC for 16 hours. The samples were wrapped in plastic to retain moisture and allowed to thaw at room temperature for eight hours. The plastic wrap was then removed and the samples were allowed to drain for 16 hours before being tested with the rapid triaxial test apparatus. Both vacuum saturation and freeze-thaw vacuum saturation procedures allowed the sample free-draining after saturation (Berthelot et al. 2010c).

The British Board of Agreement (BBA) protocol for vacuum saturation involves significantly more saturation cycles at varying temperatures. The BBA protocol involves vacuum saturating the compacted or cored sample (hot mix asphalt or granular material) in 20ºC water bath for 30 minutes, removing it, placing the sample in 60ºC water bath for 6 hours, removing it, placing the sample in 5ºC water bath for 16 hours, removing it, placing it in a 20ºC water bath for two hours, and testing the specimen for stiffness (BBA 2008). This entire process is repeated once.

3.1.8 Triaxial Frequency Sweep Test (Rapid Triaxial Test)

The rapid triaxial test (RaTT) employs triaxial frequency sweep analysis to determine mechanistic material properties under realistic field state conditions. The RaTT was developed by the Texas Transportation Institute and has been used in numerous studies to assess the mechanistic structural behaviour of pavement materials including HMAC, granular base materials, subbase materials, stabilized HMAC, stabilized granular materials, and recycled materials (Adu-Osei et al. 2000, Carpenter and Vavrik 2001, Anthony 2007, Baumgartner 2005, Berthelot 1999, Berthelot et al. 2003, Berthelot et al. 2008a, Berthelot et al. 2009a, Berthelot et al. 2009b, Berthelot et al. 2010c, Berthelot et al. 2010d, Gould et al. 2003, Little 2003, Lytton 2000).

The RaTT has a pneumatic operating system that applies confining stress and sinusoidal axial load at varying frequencies. The RaTT subjects a material specimen to field state conditions including varying load frequencies and stress states. The axial load simulates vehicle loading and the frequency of the axial load simulates traffic speed. The confinement pressure simulates confinement within a pavement structure. A cylindrical specimen is placed in the RaTT when the confining cell is raised, as illustrated in Figure 3.6.

Materials specimens used in the RaTT are gyratory compacted and are 150 mm diameter by 150 mm tall. When the cell is lowered, a rubber membrane surrounding the specimen applies a constant confining pressure. An axial load is applied on top of the sample at varying frequencies. The stress states and frequencies are controlled by a computer attached to the RaTT. Four linear variable differential transducers (LVDTs) measure the vertical and horizontal strains in the specimen.

Since the RaTT is controlled by a computer and software system, material properties are recorded throughout the test, directly from the measurements. The RaTT is capable of quantifying the time-dependent response and the stress-dependent response of the material, both of which are important for pavement design (Adu-Osei et al. 2000). Stress states and confining pressures can be adjusted using the software program to customize the test to suit applicable field state conditions or material requirements, as illustrated in Figure 3.7 (Adu-Osei et al. 2000, Little 2003).

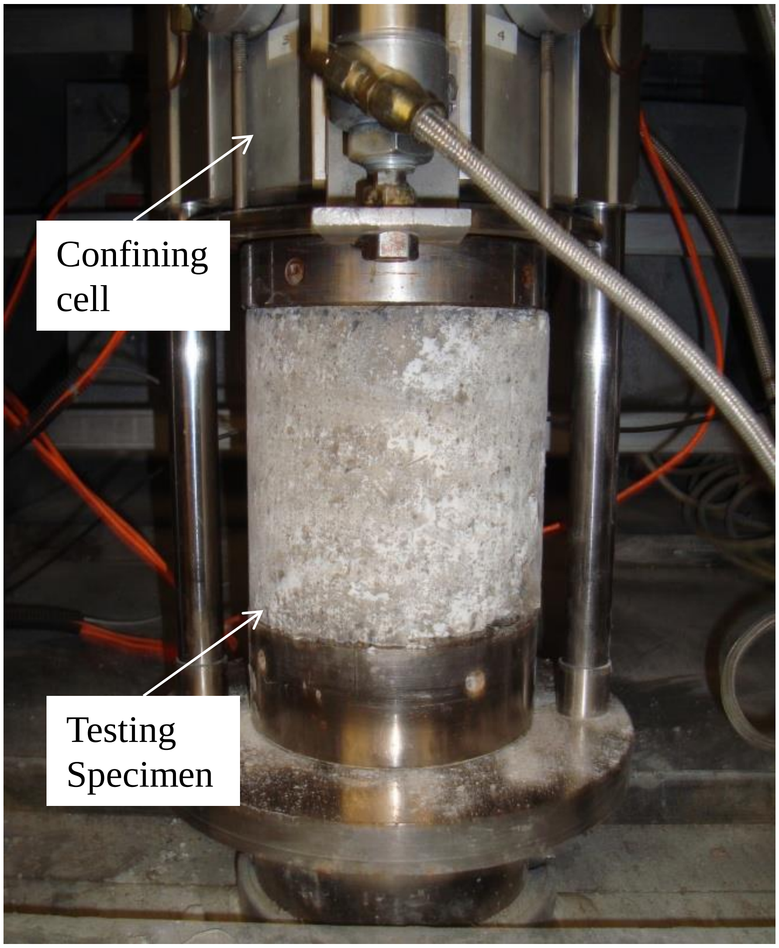


Figure 3.6 Triaxial Frequency Sweep RaTT at University of Saskatchewan

The RaTT provides a number of advantages when compared to traditional laboratory performance tests (Adu-Osei et al. 2000, Anthony 2007, Baumgartner 2005, Berthelot 1999, Berthelot et al. 2003, Berthelot et al. 2009c, Gould et al. 2003, Little 2003, Lytton 2000, Xu 2008). Advantages include:

- The RaTT is an efficient test that is conducted in a short time.
- The samples are the same size as gyratory compacted samples.
- The specimens are conserved after the RaTT test.
- The RaTT test has good repeatability.
- The RaTT is fully computer controlled.
- Specimens that can be tested in the RaTT include bound and unbound materials (HMAC and granular base, for example) and also include the addition of stabilizers such as lime, cement, and emulsion.
- Material properties determined from the RaTT are determined directly from the measurements.
- The materials properties characterized during the RaTT correlate with field measurements and are more accurate than other test methods.
- The specimens are tested under a range of frequencies, confinement conditions, and stress states representative of field state conditions.
- The RaTT test is fully automated and controlled by software.
- The test can be conducted at different temperatures.

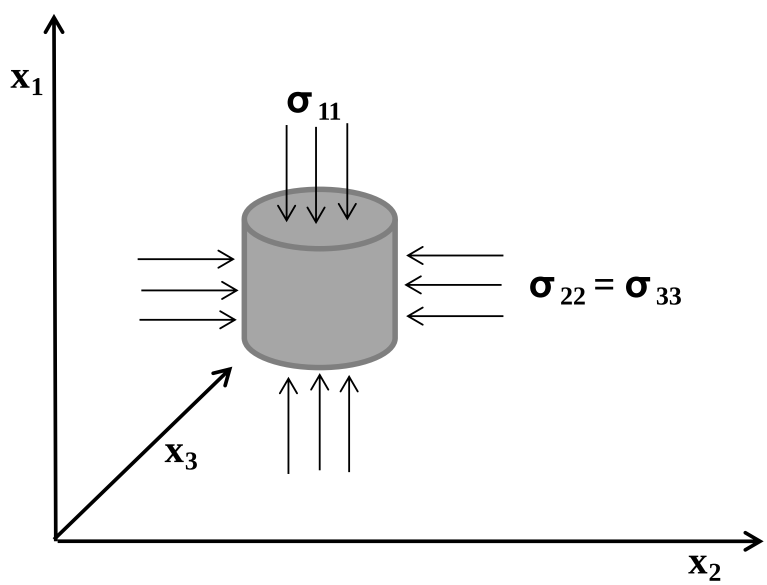


Figure 3.7 Application of Stresses during Triaxial Frequency Sweep RaTT (reproduced from Anthony 2007)

The RaTT was designed as a continuum mechanics test and obeys St. Venant's principles (Baumgartner 2005, Berthelot 1999). The RaTT provides a uniform distribution of stress and is capable of measuring the time and stress dependent response of a material. Triaxial frequency sweep testing is capable of evaluating the following fundamental material properties: dynamic modulus, Poisson's ratio, and phase angle.

3.1.8.1 Dynamic Modulus

Dynamic modulus is a measure of material stiffness under dynamic loading. It is the primary material property used by pavement designers and for use in structural road modeling (Berthelot et al. 2009c). The dynamic modulus for viscoelastic materials (E_D) is defined as the absolute value of the complex modulus (E^*), or the ratio of the peak stress and peak strain of a material. The complex modulus is defined as the ration of amplitude of time-dependent sinusoidal stress applied to the material to amplitude of time-dependent sinusoidal strain resulting from stress application (Pellinen and Witczak 2002). The dynamic modulus relationship is defined in Equation 3.2 and the complex modulus relationship is defined in Equation 3.3:

$$\boldsymbol{E_D} = |\boldsymbol{E}^*| = {\boldsymbol{\sigma_P}}/{\boldsymbol{\varepsilon_P}} \tag{3.2}$$

$$\boldsymbol{E}^* = {\boldsymbol{\sigma_P}}/{\boldsymbol{\varepsilon_P}} = \frac{\boldsymbol{\sigma_{11}e^{i\omega t}}}{\boldsymbol{\varepsilon_{11P}e^{i(\omega-\delta)}}} \tag{3.3}$$

where:

E_D = dynamic modulus (Pa),

E^* = complex modulus (Pa),

σ_P = applied peak stress (Pa,)

ε_P = peak strain response to applied stress (μm/μm),

σ_{11P} = applied peak stress in X_1 direction (Pa),

ε_{11P} = peak strain response to applied stress in X_1 direction (μm/μm),

e = exponent e,

I = imaginary component,

ω = angular load frequency (radians per second),

t = load duration (seconds), and

δ = phase angle (radians).

Although resilient modulus is typically used to characterize unbound granular materials, RAP may not be considered an unbound material. RAP is considered a viscoelastic material due to its residual asphalt cement content and dynamic modulus can be used to characterize its material properties (Berthelot et al. 2008a, Berthelot et al. 2010d, Xu 2008).

3.1.8.2 Poisson's Ratio

Poisson's ratio influences the behaviour of a material within the road structure and is required to characterize the mechanistic behaviour of pavement layers (Baumgartner 2005, Berthelot 1999, Berthelot et al. 2009c, Lytton 2000). Poisson's ratio of a material depends on its stiffness. With RaTT testing, the radial and axial strains are monitored directly. Poisson's ratio is a measure of the ratio of radial strain to axial strain and is presented in Equation 3.4:

$$\boldsymbol{\vartheta_{11}(t) = \frac{\varepsilon_{22}(t)}{\varepsilon_{11}(t)} = \frac{\varepsilon_{33}(t)}{\varepsilon_{11}(t)}} \qquad \textbf{(3.4)}$$

where:

ϑ = Poisson's ratio in X_1 coordinate direction,

$\boldsymbol{\varepsilon}_{11}$ = Strain in X_1 coordinate direction (axial),

$\boldsymbol{\varepsilon}_{22}$ = Strain in X_2 coordinate direction (radial), and

$\boldsymbol{\varepsilon}_{33}$ = Strain in X_3 coordinate direction (radial).

3.1.8.3 Phase Angle

Phase angle is measured as the shift in time of the resulting strain due to the applied stress, as illustrated in Figure 3.8 (Berthelot 1999). Phase angle can be expressed as presented as:

$$\delta = \frac{t_i}{t_p}(360°) \qquad \textbf{(3.5)}$$

where:

δ = Phase angle (degrees),

t_i = time lag between cycle of sinusoidal stress and cycle of strain (seconds), and

t_p = time lag for a stress cycle (seconds).

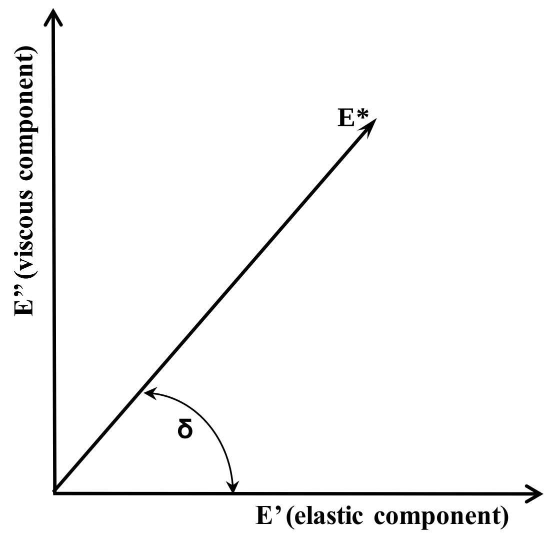


Figure 3.8 Phase Angle (Polar Coordinates) (courtesy of Dr. Berthelot's CE 417 Notes)

Phase angle can be used to indicate the viscoelastic properties of the material tested in the RaTT (Anthony 2007, Berthelot 1999, Berthelot et al. 2009c, Xu 2008). Permanent deformation behaviour has been determined based on phase angle values in certain studies (Berthelot et al. 2009c, Salifu 2010). For instance, a purely elastic response is indicated by a phase angle of 0 degrees and a purely viscous response is indicated by a phase angle of 90 degrees.

3.1.9 Significance of Laboratory Tests for RAP Systems

There are no standard specifications, testing protocols, or performance indicators for RAP materials. Various material testing and laboratory performance protocols provide different methods of assessing the performance of RAP materials in pavement base layers. Laboratory test limitations exist and field performance is not always correlated to laboratory tests. Using conventional laboratory tests to indicate the performance of RAP materials limits the use of RAP in the field. A summary of recommended laboratory tests and their significance in indicating the performance of RAP systems is presented herein.

Aggregate gradation and angularity influence the mechanical properties of a base layer and are important to its field performance. Compaction, stiffness, and sensitivity to moisture depend on particle size, shape, and gradation. The aggregate gradation of a RAP system should be comparable to a virgin base aggregate.

Proctor compaction is a test designed for unbound materials, therefore Proctor compaction does not provide adequate compacted or density of RAP materials. RAP materials resist impact compaction. Proctor compaction does not accurately replicate field compaction for both granular materials and RAP materials. The CBR test is empirically based, uses Proctor compaction, and was designed for bound aggregates. Since RAP materials resist Proctor compaction, the CBR testing results for RAP are low when compared to virgin aggregates.

Gyratory compaction provides laboratory compaction representative of field compaction and provides densities achieved in the field. Gyratory compaction is a preferred method of compaction for mechanical tests such as the rapid triaxial test.

Resilient modulus and permanent deformation testing evaluates the performance of materials under stress states, moisture conditions, and densities under a moving load, representative of pavement layer field conditions. Material properties of this test are used in recently developed mechanistic empirical pavement design guides. Both gyratory compaction and vibratory hammer compactions are used for this test. RAP materials responded well to resilient modulus and permanent deformation testing.

The RaTT has been used to characterize the mechanistic structural behaviour and performance of unbound and bound materials, including granular aggregates and hot mix. The RaTT has been used in numerous studies to assess the performance and the mechanistic material properties of pavement materials including HMAC, granular base materials, subbase materials, and recycled materials. Baumgartner (2005) identified that these past studies have found that "triaxial frequency sweep characterization in the RaTT [is] a significant improvement over traditional empirical as well as mechanistic-empirical characterization methods." Research conducted by Berthelot (1999) identified a significant difference between asphalt concrete mixes. Likewise, the study by Baumgartner (2005) found that the RaTT provides reasonable asphalt concrete material properties and adequately simulates Saskatchewan field state conditions. Xu (2008) used the RaTT to characterize mechanistic material properties of granular materials stabilized with and without cement-emulsion. Lytton (2000) identified the RaTT to be a simple test that is precise and repeatable.

The RaTT subjects a material specimen to field state conditions including varying load frequencies and stress states. The RaTT is well-developed in Saskatchewan with regards to replicating field state condition and assessing actual field performance of materials used in road construction.

3.2 Materials

The conventional granular base used in this research was a typical granular base retrieved from the City of Saskatoon Nicholson Yard stockpile.

Reclaimed asphalt pavement (RAP) rubble materials used in this research included a well graded (GW) RAP crushed in 2008, an open graded base course (OGBC) RAP crushed in 2008, a GW RAP crushed in 2009, and an OGBC crushed in 2009. The RAP materials were local to City of Saskatoon (COS) and were retrieved from COS public works; stockpiled and crushed at COS Nicholson Yard. RAP materials crushed in 2008 were crushed with the first generation of impact crusher set up (two RAP materials were produced). RAP materials crushed in 2009 were crushed with a second generation of impact crusher set up. This included additional screening and a grizzly, which reduced fines content and created three (3) RAP materials simultaneously. In addition, material processing was implemented prior to impact crushing in 2009. This included material stockpile separation prior to impact crushing.

All granular and RAP materials were sampled in accordance with ASTM D75, *Standard Practice for Sampling Aggregates*.

Stabilization materials included Type 10 cement and a slow-setting type 1 (SS-1) emulsion. Type 10 cement is an all-purpose cement typically used in soil and base stabilization for road structures. No other types of cement were used in this research. Type 10 cement was purchased locally. SS-1 emulsion is a slow setting emulsion with low viscosity that is typically used in cold processes for mixing stability in road rehabilitation and reconstruction, including full depth reclamation and base layer stabilization. No other types of emulsions were used in this research. SS-1 emulsion was purchased from a local supplier.

3.3 Test Plan and Procedures

The test setup and procedures used in this research's experimental program are outlined in the following sections.

3.3.1 Conventional Laboratory Characterization

The conventional granular base and the 2008 RAP materials were characterized first to establish if the conventional laboratory tests were applicable for RAP materials. Conventional physical properties included physical aggregate properties specified by the City of Saskatoon base aggregate specification, as listed below. The residual asphalt content of the RAP was also evaluated using ignition oven testing (ASTM D6307). The organic content of the granular base materials was determined using ignition oven testing also.

- Aggregate gradation (ASTM C117 and C136)
- Coarse aggregate angularity (ASTM D5821)
- California bearing ratio (CBR), unsoaked (ASTM D1883)

Gradation analysis (ASTM C117 and C136) and residual asphalt content determination by ignition oven (ASTM D6307) were carried out for the 2009 crushed GW and OGBC materials.

3.3.2 Mechanistic Rapid Triaxial Testing

Mechanistic rapid triaxial testing (RaTT) laboratory characterization was first conducted using the 2008 crushed reclaimed asphalt pavement (RAP) rubble materials stabilized with and without cement and/or emulsion to determine stabilizer types and amounts for repeat samples strengthening analysis of RAP materials. Two 2008 crushed RAP rubble materials were characterized: a well graded (GW) RAP material and an open graded base course (OGBC) RAP material. One sample of each of the 2008 crushed GW and OGBC RAP materials were tested in the RaTT under the following stabilization systems:

- One, two, and three percent cement;
- One, two, and three percent SS-1 emulsion; and

- Fifty-fifty splits of each stabilizer up to one, two, and three percent cement with SS-1 emulsion.

One sample of conventional granular base was also tested in the RaTT for comparison purposes.

RaTT testing protocols were conducted in accordance with those derived through various studies at the University of Saskatchewan (Anthony 2008, Baumgartner 2005, Berthelot and Gerbrandt 2002, Berthelot et al. 2003, Berthelot et al. 2009c, Salifu 2010, Xu 2008). RaTT testing was conducted on gyratory compacted specimens that were compacted according to a modified standard (SHRP) Level One gyratory compaction (AASHTO TP-4). Modifications were made to this testing standard to accommodate the RAP materials.

- RAP, emulsion, and cement materials were cold-mixed.
- The materials and the gyratory mold were not heated prior to compaction.

Material sample specimens compacted in the gyratory compactor were 150 mm in diameter and 150 ± 5 mm in height, and were compacted at 20ºC. Gyratory compaction testing parameters included a vertical pressure of 600 kPa applied to the specimen with an angle of gyration 1.25 degrees. Specimens were compacted to a target density.

Gyratory compacted specimens were moist cured for a minimum of 28 days in a moist cure room prior to rapid triaxial frequency sweep testing in the RaTT. Figure 3.9 illustrates typical gyratory compacted specimen prepared for RaTT testing. (Note that the sample is tagged *first generation recycled asphaltic concrete*. This refers to the well graded (GW) crushed RAP rubble.)

RaTT testing was done at room temperature of 20ºC and at four stress states and four frequencies, representative of COS field state conditions. The testing temperature of 20°C was chosen due to lack of resources to test at additional temperatures. As shown in Table 3.2, the four stress states were carried out sequentially, from low, to medium, to high, and fully reversed. Each stress state was carried out at four frequencies, from high frequency to low frequency: 10 Hz, 5 Hz, 1 Hz, and 0.5 Hz. The stress states were chosen based on past testing regimes representative of field state conditions in Saskatchewan. It was possible for a material specimen to fail at any given stress state and frequency. For example, if a specimen failed after the last frequency at the low stress state, triaxial frequency sweep testing was complete and the specimen was removed from the RaTT. The material properties determined by the RaTT include: dynamic modulus, Poisson's ratio, phase angle, and radial microstrain.

Figure 3.9 Gyratory Compacted GW RAP Specimen for RaTT Testing (courtesy of PSI Technologies)

Table 3.2 Triaxial Frequency Sweep Testing Parameters

Stress State	Testing Sequence	Vertical Traction (kPa)	Confinement Traction (kPa)	Deviatoric Stress (kPa)	Load Frequency (Hz)
Low	1	450	250	200	10
	2	450	250	200	5
	3	450	250	200	1
	4	450	250	200	0.5
Medium	5	650	250	400	10
	6	650	250	400	5
	7	650	250	400	1
	8	650	250	400	0.5
High	9	650	100	550	10
	10	650	100	550	5
	11	650	100	550	1
	12	650	100	550	0.5
Fully Reversed	13	50, 450	250	±200	10
	14	50, 450	250	±200	5
	15	50, 450	250	±200	1
	16	50, 450	250	±200	0.5

RaTT laboratory characterization was then conducted using the 2009 crushed RAP rubble materials. This set of testing used five repeat samples of GW RAP and OGBC RAP stabilized with these stabilization materials:

- Two percent cement;
- Two percent slow-setting (SS-1) emulsion; and
- One percent cement with one percent SS-1 emulsion.

No additional sample(s) of conventional granular base were tested in the RaTT with the 2009 RAP materials.

Material sample specimens compacted in the gyratory compactor were 150 mm in diameter and 150 ± 5 mm in height, and were compacted at 20ºC. Gyratory compaction testing parameters included a vertical pressure of 600 kPa applied to the specimen with an angle of gyration 1.25 degrees. Specimens were compacted to a target density.

All materials samples were moist cured for a minimum of 28 days in a moist cure room prior to rapid triaxial frequency sweep testing in the RaTT. RaTT testing protocols for the 2009 GW and OGBC RAP materials were the same as used for the 2008 GW and OGBC RAP materials. RaTT testing temperature of 20°C was chosen because it is representative of optimal field state conditions in the City of Saskatoon.

Following moist cure triaxial frequency sweep testing, samples were subjected to climatic conditioning using vacuum saturation as described in section 3.1.7 and detailed by Berthelot et al. (2010c). Figure 3.10 illustrates sample preparation for vacuum saturation. The purpose of the vacuum was to remove the air from the chamber, allowing the specimen to saturate with water. The specimens were saturated under vacuum for eight hours, at room temperature. The water was then removed from the chamber and the specimen was drained for 16 hours. Following draining, the specimen was removed from the chamber and tested in the RaTT. Vacuum saturation was conducted at 20ºC.

Following vacuum saturation, samples were tested again using triaxial frequency sweep testing protocol, as previously described. It was possible for a material specimen to fail after vacuum saturation. For example, if a specimen failed in vacuum saturation, it fell apart by crumbling upon removal from the saturation chamber and post vacuum saturation frequency sweep testing was not possible. It was also possible for a material specimen to fail at any given RaTT stress state and frequency. For example, if a specimen failed after the last frequency at the low stress state, triaxial frequency sweep testing was complete and the specimen was removed from the RaTT.


a) Saturation chamber **b) Sample placed in chamber**


c) Saturation water added to chamber **d) Vacuum applied to sample**

Figure 3.10 Vacuum Saturation Sample Preparation (photos taken by the author)

3.4 Chapter Summary

This chapter presented laboratory characterization background for reclaimed asphalt pavement (RAP) materials. This chapter also detailed the materials and testing plan and procedures used in this research.

The aggregate gradation test, Proctor compaction method, gyratory compaction method, California bearing ratio (CBR) test, resilient modulus and permanent deformation test, tube suction test (TST), vacuum saturation test, and triaxial frequency sweep test (RaTT) were discussed with regards to limitations and their ability to adequately represent RAP performance in the field. Proctor compaction and CBR testing are not recommended for laboratory characterization of RAP materials, which is considered a bound material. It was found that gyratory compaction provides laboratory compaction representative of field compaction and densities achieved in the field.

Although RAP materials responded well to resilient modulus and permanent deformation testing, the RaTT is recommended to characterize the mechanistic structural behavior of RAP materials. The RaTT has been used in numerous studies to assess the performance and the mechanistic material properties of pavement materials including HMAC, granular base materials, subbase materials, and recycled materials. The RaTT is well-developed in Saskatchewan with regards to replicating field state condition and assessing actual field performance at materials use in road construction. The RaTT is also capable of characterizing the viscoelastic component of materials, which is applicable to RAP materials.

CHAPTER 4 PRELIMINARY LABORATORY CHARACTERIZATION OF 2008 CRUSHED RAP RUBBLE MATERIALS

Preliminary laboratory characterization of 2008 crushed reclaimed asphalt pavement (RAP) rubble materials was conducted to establish if conventional laboratory tests were applicable for the RAP materials and to determine stabilizer types and amounts for repeat samples strengthening analysis of 2009 crushed RAP rubble materials.

Conventional physical properties included physical aggregate properties specified by the City of Saskatoon base aggregate specification. Mechanistic rapid triaxial testing (RaTT) laboratory characterization was conducted using the 2008 crushed reclaimed asphalt pavement rubble materials stabilized with and without cement and/or emulsion.

Two RAP materials were crushed using the impact crusher is 2008: a well graded (GW) and an open grade base course (OGBC). The RAP feedstock material was not processed or separated prior to placing it in the impact crusher.

4.1 RAP Aggregate Gradations

Gradation and aggregate angularity influence the mechanical properties of a pavement layer. Gradation influences the moisture and frost susceptibility, durability, and stiffness of an unbound aggregate layer. Figure 4.1 illustrates the gradations of the well graded (GW) and open graded base course (OGBC) reclaimed asphalt pavement (RAP) materials, as well as the conventional granular base material.

The conventional COS granular base gradation met the COS base aggregate gradation specification but was not represented by a smooth particle-size distribution curve; the fine portion of the conventional granular base gradation followed the lower bandwidth of the COS specification and the coarser portion of the conventional granular base gradation followed the upper bandwidth of the COS specification. The GW RAP gradation was represented by a smooth particle-size distribution within the COS base aggregate specified limits and had evenly distributed particles; this is why this material was referred to as *well graded* (GW) material. The OGBC RAP gradation did not meet the COS base aggregate specified limits and was composed of reduced fines content and increased large, coarse particles; this is why this material was referred to as *open graded base course* (OGBC) material.

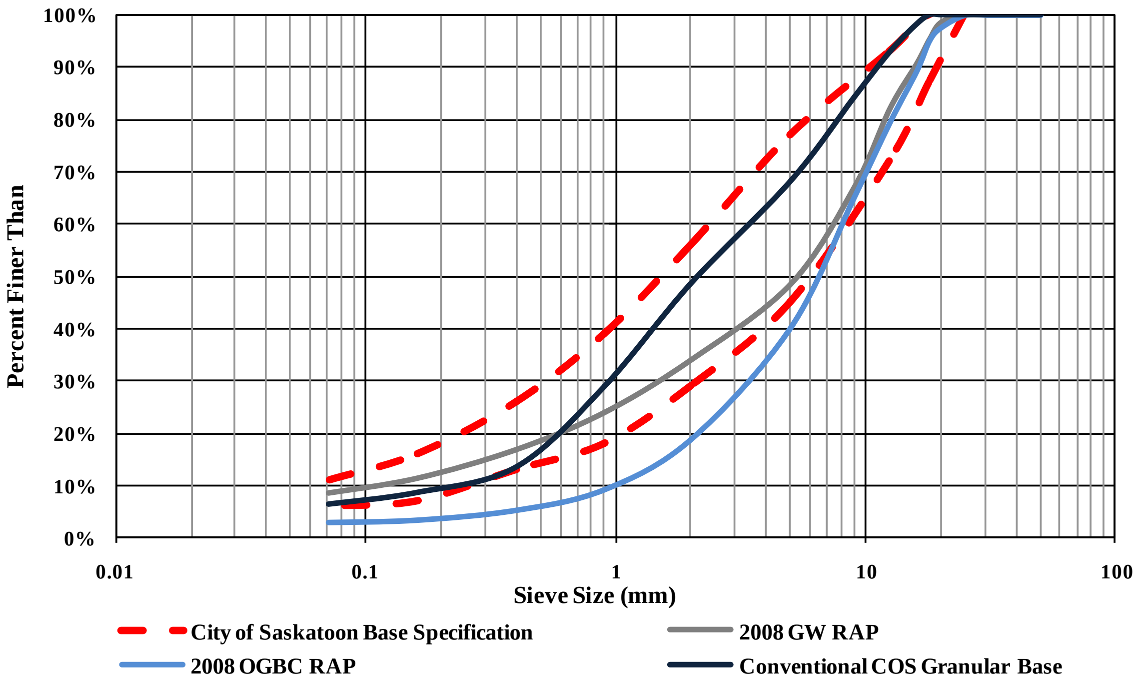


Figure 4.1 Gradations of 2008 GW and OGBC RAP

The COS base aggregate specification limits specify a crushed material top size of 18 mm (COS 2005). However, the crushed GW and OGBC RAP had top sizes of 19 mm and 25 mm, respectively. This is due to the impact crushing methodology used to crush the RAP rubble materials.

The COS base aggregate specification limits has a fines content bandwidth of six to eleven percent, defined as the material passing the 71 µm sieve (COS 2005). The crushed GW RAP had a greater portion of fines and fine sand content when compared to the crushed OGBC RAP. This was expected as the OGBC RAP had a coarser gradation with larger-sized particles and reduced fines and fine sand content. The fines and fine sand content of the GW RAP were within the COS base aggregate specification limits for material passing the 71 µm sieve (COS 2005).

4.2 Coarse Aggregate Angularity

The City of Saskatoon base aggregate specifications require at least 50 percent of the material (by weight) retained on the 5 mm sieve to have one or more fractured faces created by crushing (COS 2005). Table 4.1 lists the percent of material retained on the 5 mm sieve with one fractured face or more, for one sample of each of the conventional City granular base, 2008 GW RAP, and 2008 OGBC RAP. The conventional granular base did not meet the minimum 50 percent requirement; whereas the GW and OGBC crushed RAP exceeded the minimum City of Saskatoon fractured face requirement with 53 percent and 72 percent fractured faces, respectively.

Table 4.1 Particles Retained on the 5 mm Sieve with Fractured Faces for 2008 GW and OGBC RAP

Base Material	Particles Retained on the 5 mm Sieve
Conventional Granular Base	48%
2008 GW RAP	53%
2008 OGBC RAP	72%

The OGBC crushed RAP had more fractured faces compared to the GW crushed RAP and the conventional granular base. This is due to an increased top size, reduced fines content, and more angular particles resulting from the impact method of aggregate crushing. Processing and crushing RAP aggregates can increase the number of fractured faces of a RAP particle (Deniz et al. 2010, Garg and Thompson 1996, MacGregor et al. 1999, NCHRP 2008, Robinson et al. 2004, Senior et al. 2008). Aggregate angularity influences the number of fractured faces of aggregate particles and particle interlock during compaction.

4.3 Standard Proctor Compaction Test

Standard Proctor compaction testing was conducted in accordance with ASTM D698 (ASTM 2007). The purpose of the standard Proctor compaction test is to determine the optimum moisture content and maximum dry density of a soil. Although testing protocol states that soil(s) used in a Proctor compaction test are to be “natural occurring” (ASTM 2007), the test was carried out in the preliminary portion of this research on the crushed RAP rubble material. RAP is not considered to be a naturally occurring material because it is composed of aggregate and asphalt cement. A conventional granular base was also tested to compare to the RAP.

Table 4.2 lists Proctor compaction test results for one sample each of the conventional granular base and 2008 OGBC RAP. The GW RAP was Proctor compacted, however a Proctor compaction curve could not be achieved. It was observed that the mold expelled moisture during impact Proctor compaction and the RAP specimens were loosely compacted when removed from the molds for CBR testing. This may be due to the low mineral fines and asphalt cement content in the RAP, which can resist impact compaction. The conventional granular base materials had a higher optimum moisture content compared to the RAP materials because conventional granular base materials absorb some moisture during compaction. Since asphalt cement coats the aggregate particles, less moisture is absorbed into the RAP material.

Table 4.2 Proctor Compaction Test Results for 2008 GW and OGBC RAP

Base Material	Maximum Dry Density (kg/m^3)	Optimum Moisture Content
Conventional Granular Base	2220	6.5%
2008 OGBC RAP	2200	1.9%

Literature revealed typical Proctor maximum dry densities to range from 1600 kg/m^3 to 2100 kg/m^3 for 100 percent RAP material and full depth reclamation RAP/aggregate blends (Deniz et al. 2010, Guthrie et al. 2007a, Jeon et al. 2009, Schaertl and Edil 2009, Kim et al. 2007, Senior et al. 2008, Taha et al. 2002). Optimum moisture contents varied from as low as two to five percent for 100 percent RAP specimens to as high as 10.4 percent optimum moisture content for a FDR RAP/aggregate blend (Deniz et al. 2010, Jeon et al. 2009, Kim et al. 2007).

4.4 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) test is an empirical strength test that compares the strength of an unbound material to crushed limestone and is outlined in ASTM D1883 (ASTM 2007). The City of Saskatoon specifies a minimum CBR of 65 in the unsoaked condition for base aggregate compacted to 100 percent of the maximum density, determined by standard

Proctor compaction (COS 2005). Proctor compaction and CBR testing were used to evaluate the CBR of conventional granular base, GW RAP, and OGBC RAP.

The 2008 GW RAP and OGBC RAP specimens (compacted in the Proctor mold) were used then used for California Bearing Ratio (CBR) testing. Table 4.3 lists the unsoaked CBR values for the conventional granular base, GW RAP, and OGBC RAP.

Table 4.3 Unsoaked CBR for 2008 GW and OGBC RAP

Base Material	Unsoaked CBR
Conventional Granular Base	77%
2008 GW RAP	14%
2008 OGBC RAP	3%

The City of Saskatoon specifies a minimum CBR of 65 and the conventional granular base exceeded that with a CBR of 77 percent. The crushed GW RAP and the OGBC RAP did not meet the specified CBR of 65 percent. The CBR values for the crushed GW RAP and OGBC RAP were low compared to the conventional granular base. The OGBC RAP had a CBR value less than that of the GW RAP. It is hypothesized that this was due to the coarseness of the material and minimal amount of fines content, which reduced compactness of the material by impact. Although the RAP materials remained intact in the Proctor mold, it was observed that during Proctor compaction the mold expelled moisture and upon removal from the mold, the RAP specimens seemed loosely compacted. Therefore, impact Proctor compaction may not be appropriate for RAP materials. Literature revealed typical CBR values for 100 percent RAP to be between 11 percent and 25 percent (Schaertl and Edil 2009, Taha et al. 1999).

4.5 Residual Asphalt Content Using Ignition Oven

The mass loss on ignition of the virgin granular base materials is attributed to organic content and is limited to five percent by weight for City of Saskatoon base aggregates (COS 2005). The mass loss on ignition of crushed RAP materials is attributed to residual asphalt content. Table 4.4 lists the mass loss on ignition of the virgin granular base, GW RAP, and OGBC RAP.

Table 4.4 Material Loss on Ignition for of 2008 GW and OGBC RAP

Base Material	Material Loss on Ignition
Conventional Granular Base	1.0%
2008 GW RAP	5.5%
2008 OGBC RAP	6.3%

The virgin granular base had one percent organic content, which was less than the COS specified maximum of five percent organic content. The GW RAP and OGBC RAP materials had 5.5 percent and 6.3 percent residual asphalt concrete, respectively. The City does not employ a granular base specification with regards to permissible residual asphalt content. The OGBC RAP has a higher residual asphalt content compared to the GW RAP because the OGBC RAP was composed of larger particles which were coated with asphalt. This is a result of the impact crushing and screening process.

4.6 Mechanistic Material Property Characterization

Mechanistic material property characterization was carried out using triaxial frequency sweep by the rapid triaxial tester (RaTT) at the University of Saskatchewan. Background information on the RaTT is presented in Chapter Two. The rapid triaxial testing was performed on GW RAP and OGBC RAP stabilized with one, two, and three percent each of cement and slow-setting (SS-1) emulsion, and fifty-fifty splits of each stabilizer for up to one, two, and three percent cement with SS-1 emulsion blends. One sample of each stabilization system was tested as a preliminary strengthening analysis; the purpose of preliminary strengthening analysis was to examine the mechanistic behaviour and performance of stabilized crushed RAP rubble materials and compare it to the behaviour of conventional granular base materials.

Only the results for the low and high stress states are presented herein for discussion. (Stress states are detailed in Chapter Three.) Complete RaTT results for all stress states are included in Appendix A.

4.6.1 Specimen Preparation

Granular base, and GW and OGBC RAP materials specimens were prepared and compacted in the gyratory compactor at 20°C. Specimens were 150 mm in diameter and 150 ± 5 mm in height. The target density was set equal to the maximum dry density of the materials under optimum moisture content, listed in Table 4.5. The values for the conventional granular base and the 2008 OGBC RAP were chosen based on the Proctor compaction results. For the 2009 GW RAP, the maximum dry density was reduced slightly and the optimum moisture content was increased slightly compared to the 2008 OGBC RAP values.

Table 4.5 Target Dry Density for Gyratory Compaction

Base Material	Maximum Dry Density (kg/m^3)	Optimum Moisture Content
Conventional Granular Base	2220	6.5%
2008 GW RAP	2170	3.2%
2008 OGBC RAP	2200	1.9%

All materials samples were moist cured for a minimum of 28 days in a moist cure room prior to rapid triaxial frequency sweep testing in the rapid triaxial tester (RaTT), conducted at 20°C.

4.6.2 Specimen Failure

A material specimen could fail at any given RaTT stress state and frequency. For example, if a specimen failed after the last frequency at the low stress state, triaxial frequency sweep testing was complete and the specimen was removed from the RaTT.

During triaxial frequency sweep by RaTT, the conventional granular base specimen failed after the 10 Hz frequency sweep at the high stress state. This has been shown in previous triaxial frequency sweep testing of Saskatchewan granular base materials (Berthelot et al. 2009c, Xu 2008). All stabilized GW and OGBC RAP specimens remained intact during the full testing sequence of the RaTT. No GW RAP or OGBC RAP material samples failed in the RaTT.

4.6.3 Dynamic Modulus Characterization

Dynamic modulus is a measure of the stiffness of a material under dynamic loading and is represented by the ratio of the absolute value of peak stress to peak strain in RaTT testing.

Further description of dynamic modulus as it relates to triaxial frequency sweep testing was provided in Chapter Two. Table 4.6 presents the dynamic modulus of 2008 GW crushed RAP rubble material stabilized with cement and/or SS-1 emulsion across low and high stress states. Table 4.7 presents the dynamic modulus of the 2008 OBGC crushed RAP rubble material stabilized with cement and/or SS-1 emulsion across low and high stress states.

The unstabilized GW and OGBC RAP materials had dynamic modulus values higher than the conventional COS granular base material, across all stress states and frequencies, demonstrating that RAP materials are stiffer under the same loads, when compared to granular materials. Higher induced stresses on the specimens resulted in improved stiffness of the OGBC RAP, as compared to the GW RAP. Cement and/or SS-1 emulsion stabilization of the RAP materials further increased the stiffness of the material, compared to unstabilized RAP materials and the conventional granular base, across all stress states and frequencies.

The highest dynamic modulus for cement stabilized GW RAP was measured at a concentration of one percent cement. The GW RAP did not increase in stiffness with an increase in cement concentration. Both one percent and two percent cement stabilization performed similarly; applying a concentration of one percent cement is difficult in the field; therefore, two percent cement stabilization for GW RAP is recommended for ease of application in the field.

Two and three percent SS-1 emulsion stabilized GW RAP samples resulted in greater dynamic modulus when compared to two and three percent cement stabilized GW RAP samples, across all stress states and frequencies. At the low stress state, the dynamic modulus of the two percent SS-1 emulsion stabilized GW RAP sample was greater than the dynamic modulus of the three percent SS-1 emulsion stabilized GW RAP sample, across all frequencies.

Table 4.6 2008 GW RAP Dynamic Modulus across Two Stress States

Base Material and Stabilization System	Dynamic Modulus (MPa)			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	479	480	488	491
Unstabilized GW RAP	1111	1073	960	928
1.0% Cement GW RAP	1827	1772	1662	1664
2.0% Cement GW RAP	1782	1836	1714	1715
3.0% Cement GW RAP	1621	1606	1532	1516
1.0% SS-1 GW RAP	1658	1608	1405	1332
2.0% SS-1 GW RAP	2157	2091	1789	1667
3.0% SS-1 GW RAP	2055	1960	1704	1605
1.0% Cement, SS-1 GW RAP	1606	1601	1447	1420
2.0% Cement, SS-1 GW RAP	1914	1891	1709	1677
3.0% Cement, SS-1 GW RAP	2071	2009	1857	1790
High Stress State				
Conventional COS Granular Base	295	Failed	Failed	Failed
Unstabilized GW RAP	890	843	740	704
1.0% Cement GW RAP	1785	1620	1443	1388
2.0% Cement GW RAP	1772	1654	1487	1430
3.0% Cement GW RAP	1366	1276	1166	1146
1.0% SS-1 GW RAP	1381	1313	1096	1020
2.0% SS-1 GW RAP	1808	1691	1379	1255
3.0% SS-1 GW RAP	1860	1693	1355	1230
1.0% Cement, SS-1 GW RAP	1279	1258	1103	1033
2.0% Cement, SS-1 GW RAP	1703	1570	1345	1260
3.0% Cement, SS-1 GW RAP	1828	1708	1471	1383

At low concentrations of one percent stabilization, the GW RAP with a 50/50 split of cement with emulsion showed a minimal difference in dynamic modulus, averaged across all frequencies at the low stress state, when compared to the GW RAP with SS-1 emulsion stabilized material. At a concentration of three percent, the GW RAP with 50/50 splits of cement with emulsion showed an increase in dynamic modulus when compared to the GW RAP with SS-1 emulsion stabilization alone. This indicates an interaction of cement and SS-1 emulsion resulting in a stiffer material, when compared with SS-1 emulsion stabilization alone, for GW RAP.

Table 4.7 2008 OGBC RAP Dynamic Modulus across Two Stress States

Base Material and Stabilization System	Dynamic Modulus (MPa)			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	479	480	488	491
Unstabilized OGBC RAP	1673	1581	1344	1269
1.0% Cement OGBC RAP	1727	1691	1449	1378
2.0% Cement OGBC RAP	2022	1879	1667	1597
3.0% Cement OGBC RAP	2198	2126	1951	1889
1.0% SS-1 OGBC RAP	1747	1593	1350	1258
2.0% SS-1 OGBC RAP	1738	1663	1398	1297
3.0% SS-1 OGBC RAP	2402	2331	1824	1668
1.0% Cement, SS-1 OGBC RAP	2086	2006	1814	1682
2.0% Cement, SS-1 OGBC RAP	1841	1800	1617	1555
3.0% Cement, SS-1 OGBC RAP	2076	2101	1838	1725
High Stress State				
Conventional COS Granular Base	295	Failed	Failed	Failed
Unstabilized OGBC RAP	1206	1150	972	901
1.0% Cement OGBC RAP	1301	1248	1073	1000
2.0% Cement OGBC RAP	1624	1515	1279	1178
3.0% Cement OGBC RAP	2050	1914	1616	1500
1.0% SS-1 OGBC RAP	1373	1255	1027	947
2.0% SS-1 OGBC RAP	1573	1417	1115	1008
3.0% SS-1 OGBC RAP	2084	1873	1424	1256
1.0% Cement, SS-1 OGBC RAP	1815	1639	1349	1232
2.0% Cement, SS-1 OGBC RAP	1460	1498	1264	1171
3.0% Cement, SS-1 OGBC RAP	1697	1735	1407	1285

The OGBC RAP specimens stabilized with cement showed an increase in stiffness with increasing cement content; this differs from the GW RAP, which decreased in stiffness with increasing cement content. This may be due to the reduced fines and fine sand content in the OGBC RAP and/or the increased residual asphalt cement content of the OGBC RAP. Furthermore, the OGBC RAP specimens had coarser particles with more fracture faces than the GW RAP and conventional granular base. Particle fracture influences aggregate interlock which in turn affects a material's stiffness, as observed with the OGBC RAP specimens, which had increased stiffness compared to the GW RAP specimens. The OGBC RAP specimens with SS-1 emulsion stabilization showed an increase in stiffness with increasing SS-1 emulsion content, at both the low and high stress states. OGBC RAP specimens stabilized with cement and SS-1 emulsion blends performed similarly. Across all stress states and frequencies, the dynamic modulus of the two percent cement with SS-1 emulsion blend was less than the dynamic modulus of the one percent cement with SS-1 emulsion blend and the dynamic modulus of the three percent cement with SS-1 emulsion blend.

4.6.4 Poisson's Ratio Characterization

Poisson's ratio is a measure of the ratio of radial strain to axial strain and is directly related to the volume change of a mass of particles under a change in stress state (Lytton 2000). Table 4.8 presents the Poisson's ratio of the 2008 GW crushed RAP rubble material stabilized with cement and/or SS-1 emulsion across low and high stress states. Table 4.9 presents the Poisson's ratio of the 2008 OGBC crushed RAP rubble material stabilized with cement and/or SS-1 emulsion across low and high stress states.

The Poisson's ratio of the conventional granular base specimen was greater than the Poisson's ratios of the unstabilized and cement and/or SS-1 emulsion stabilized GW and OGBC RAP specimens, across all stress states and frequencies. Due to improved stiffness of the OGBC compared to the GW RAP, the magnitude of the unstabilized OGBC RAP Poisson's ratio is less than the GW RAP material. At a low stress state, there was a reduced sensitivity of the RAP materials to frequency. Increased sensitivity of the RAP materials to frequency was observed at a high stress state.

At a high stress state, cement and/or SS-1 emulsion stabilized GW and OGBC RAP specimens showed an increase in Poisson's ratio with decreasing frequency. At a low stress state, three percent cement stabilized GW and OGBC RAP specimens showed little sensitivity in Poisson's ratio across frequencies.

Table 4.8 2008 GW RAP Poisson's Ratio across Two Stress States

Base Material and Stabilization System	Poisson's Ratio			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	0.46	0.47	0.46	0.45
Unstabilized GW RAP	0.36	0.35	0.36	0.37
1.0% Cement GW RAP	0.19	0.22	0.26	0.23
2.0% Cement GW RAP	0.23	0.22	0.23	0.26
3.0% Cement GW RAP	0.19	0.19	0.21	0.21
1.0% SS-1 GW RAP	0.21	0.22	0.22	0.24
2.0% SS-1 GW RAP	0.19	0.23	0.23	0.22
3.0% SS-1 GW RAP	0.23	0.25	0.27	0.27
1.0% Cement, SS-1 GW RAP	0.24	0.24	0.23	0.26
2.0% Cement, SS-1 GW RAP	0.20	0.21	0.23	0.23
3.0% Cement, SS-1 GW RAP	0.22	0.17	0.21	0.19
High Stress State				
Conventional COS Granular Base	1.00	Failed	Failed	Failed
Unstabilized GW RAP	0.52	0.54	0.58	0.59
1.0% Cement GW RAP	0.33	0.34	0.37	0.38
2.0% Cement GW RAP	0.28	0.29	0.32	0.34
3.0% Cement GW RAP	0.27	0.28	0.31	0.34
1.0% SS-1 GW RAP	0.30	0.33	0.38	0.40
2.0% SS-1 GW RAP	0.28	0.29	0.34	0.36
3.0% SS-1 GW RAP	0.32	0.34	0.37	0.40
1.0% Cement, SS-1 GW RAP	0.36	0.38	0.42	0.44
2.0% Cement, SS-1 GW RAP	0.31	0.32	0.35	0.37
3.0% Cement, SS-1 GW RAP	0.25	0.27	0.30	0.33

At a high stress state, for each stabilization system, the Poisson's ratio increased with each sequential frequency sweep – a result of high stress state and frequency sweep. For example, increased Poisson's ratios were observed at a high stress state at a slow frequency (0.5 Hz) which represented the field state condition of heavy, slow moving traffic. The high stress state also emphasized the decrease in Poisson's ratio for the cement and cement with SS-1 emulsion stabilized specimens, with increasing stabilization concentrations. This was not observed in the SS-1 emulsion stabilized specimens; the Poisson's ratio decreased from one percent SS-1 emulsion concentration to two percent SS-1 emulsion concentration, but then increased at a three percent SS-1 emulsion concentration.

Table 4.9 2008 OGBC RAP Poisson's Ratio across Two Stress States

Base Material and Stabilization System	Poisson's Ratio			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	0.46	0.47	0.46	0.45
Unstabilized OGBC RAP	0.22	0.23	0.24	0.25
1.0% Cement OGBC RAP	0.24	0.30	0.29	0.31
2.0% Cement OGBC RAP	0.26	0.22	0.26	0.28
3.0% Cement OGBC RAP	0.22	0.17	0.18	0.20
1.0% SS-1 OGBC RAP	0.28	0.26	0.31	0.30
2.0% SS-1 OGBC RAP	0.26	0.27	0.28	0.28
3.0% SS-1 OGBC RAP	0.18	0.20	0.21	0.22
1.0% Cement, SS-1 OGBC RAP	0.24	0.24	0.25	0.28
2.0% Cement, SS-1 OGBC RAP	0.19	0.18	0.20	0.21
3.0% Cement, SS-1 OGBC RAP	0.23	0.21	0.20	0.21
High Stress State				
Conventional COS Granular Base	1.00	Failed	Failed	Failed
Unstabilized OGBC RAP	0.32	0.35	0.40	0.43
1.0% Cement OGBC RAP	0.30	0.33	0.37	0.40
2.0% Cement OGBC RAP	0.32	0.34	0.38	0.40
3.0% Cement OGBC RAP	0.25	0.25	0.28	0.32
1.0% SS-1 OGBC RAP	0.33	0.36	0.41	0.45
2.0% SS-1 OGBC RAP	0.31	0.34	0.38	0.41
3.0% SS-1 OGBC RAP	0.27	0.29	0.32	0.35
1.0% Cement, SS-1 OGBC RAP	0.39	0.39	0.43	0.45
2.0% Cement, SS-1 OGBC RAP	0.26	0.29	0.34	0.37
3.0% Cement, SS-1 OGBC RAP	0.26	0.29	0.34	0.36

4.6.5 Phase Angle Characterization

Phase angle is measured as the shift in time of the resulting strain due to the applied stress. Phase angle can be used to indicate the viscoelastic properties of a material. A purely elastic response is indicated by a phase angle of 0 degrees and a purely viscous response is indicated by a phase angle of 90 degrees. Table 4.10 presents the phase angle of the 2008 GW crushed RAP rubble material stabilized with cement and/or SS-1 emulsion across low and high stress states. Table 4.11 presents the phase angle of 2008 OGBC crushed RAP rubble material stabilized with cement and/or SS-1 emulsion across low and high stress states.

Table 4.10 2008 GW RAP Phase Angle across Two Stress States

Base Material and Stabilization System	Phase Angle (degrees)			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	8.6	6.9	5.3	5.1
Unstabilized GW RAP	16.1	14.3	13.3	12.3
1.0% Cement GW RAP	12.2	11.8	11.9	11.8
2.0% Cement GW RAP	13.2	11.1	10.9	10.6
3.0% Cement GW RAP	11.7	10.4	10.3	10.0
1.0% SS-1 GW RAP	15.3	14.6	12.9	13.6
2.0% SS-1 GW RAP	15.4	14.3	14.1	13.9
3.0% SS-1 GW RAP	15.5	15.7	15.0	14.9
1.0% Cement, SS-1 GW RAP	13.4	12.1	11.4	11.0
2.0% Cement, SS-1 GW RAP	12.9	12.0	11.9	11.9
3.0% Cement, SS-1 GW RAP	12.8	10.5	10.2	10.8
High Stress State				
Conventional COS Granular Base	15.2	Failed	Failed	Failed
Unstabilized GW RAP	18.9	17.2	16.0	15.3
1.0% Cement GW RAP	15.4	15.7	14.4	14.3
2.0% Cement GW RAP	17.2	14.3	14.0	14.1
3.0% Cement GW RAP	16.0	14.5	14.3	14.1
1.0% SS-1 GW RAP	18.1	16.6	16.0	15.9
2.0% SS-1 GW RAP	18.5	16.6	16.3	16.6
3.0% SS-1 GW RAP	18.9	17.4	17.2	17.3
1.0% Cement, SS-1 GW RAP	17.6	15.1	14.6	14.7
2.0% Cement, SS-1 GW RAP	16.0	15.3	14.6	14.4
3.0% Cement, SS-1 GW RAP	14.8	14.3	14.0	14.1

The phase angle of all GW and OGBC RAP specimens (unstabilized and cement and/or SS-1 emulsion stabilized) was higher than the phase angle of the conventional granular base, across stress states and frequencies prior to the conventional granular base failing. Cement stabilized GW and OGBC RAP specimens had a reduced phase angle, compared to unstabilized RAP specimens, across all frequency sweeps and stress states.

Table 4.11 2008 OGBC RAP Phase Angle across Two Stress States

Base Material and Stabilization System	Phase Angle (degrees)			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	8.6	6.9	5.3	5.1
Unstabilized OGBC RAP	15.8	13.5	13.0	13.0
1.0% Cement OGBC RAP	14.0	11.2	11.8	10.8
2.0% Cement OGBC RAP	14.1	13.3	11.8	11.5
3.0% Cement OGBC RAP	14.0	11.5	11.6	11.0
1.0% SS-1 OGBC RAP	16.6	14.8	14.2	13.8
2.0% SS-1 OGBC RAP	16.7	16.0	15.1	15.7
3.0% SS-1 OGBC RAP	18.1	16.5	16.3	16.3
1.0% Cement, SS-1 OGBC RAP	14.8	12.5	12.5	12.6
2.0% Cement, SS-1 OGBC RAP	14.8	13.1	11.7	13.2
3.0% Cement, SS-1 OGBC RAP	15.1	13.8	13.5	13.2
High Stress State				
Conventional COS Granular Base	15.2	Failed	Failed	Failed
Unstabilized OGBC RAP	16.8	15.1	14.4	14.3
1.0% Cement OGBC RAP	15.4	14.2	13.5	13.1
2.0% Cement OGBC RAP	15.8	14.7	14.4	14.1
3.0% Cement OGBC RAP	15.4	14.2	13.9	14.2
1.0% SS-1 OGBC RAP	17.2	16.7	15.9	15.9
2.0% SS-1 OGBC RAP	19.7	18.5	18.1	17.8
3.0% SS-1 OGBC RAP	20.0	19.2	18.9	18.7
1.0% Cement, SS-1 OGBC RAP	16.9	16.1	15.4	15.5
2.0% Cement, SS-1 OGBC RAP	18.4	14.8	14.3	14.4
3.0% Cement, SS-1 OGBC RAP	20.1	16.5	16.2	15.8

There was a reduction in phase angle for GW RAP stabilized with cement, SS-1 emulsion, and cement with SS-1 emulsion across low and high stress states. At a high stress state, the phase angle of the SS-1 emulsion stabilized GW RAP increased with the concentration of SS-1 emulsion. It is hypothesized that the SS-1 emulsion increases the viscous behavior of the GW RAP material, while cement stabilization reduces this behaviour.

The GW RAP specimens stabilized with cement and SS-1 emulsion had a reduced phase angle compared to the specimens stabilized with SS-1 emulsion alone. At a concentration of two percent (one percent cement with one percent SS-1 emulsion), the GW RAP had a phase angle less than the phase angle of the two percent cement.

Greater phase angles for OGBC RAP were observed compared to the GW RAP phase angles. This may be because OGBC RAP is composed of residual asphalt cement content and this increases its viscous-components.

The phase angle for OGBC RAP stabilized with SS-1 emulsion was greatest when compared to all other stabilization systems and the unstabilized specimen, across all frequencies for the low and high stress state. Again, the SS-1 emulsion may have increased the viscous behavior of the RAP material.

The cement with SS-1 emulsion stabilized OGBC RAP specimens had a reduced phase angle compared to the unstabilized specimens at a low stress state, across all frequencies. At a high stress state, the cement with SS-1 emulsion stabilized OGBC RAP specimens had an increased phase angle compared to the unstabilized specimens, across all frequencies

4.6.6 Radial Microstrain Characterization

Radial microstrain, determined by triaxial frequency sweet testing, provides an indication of the potential of a material to fail in shear (Berthelot et al. 2009d). Radial microstrain is also considered to indicate a material's resilience to edge shear failure (Berthelot 1999, Berthelot et al. 2009c, Xu 2008). Table 4.12 presents the radial microstrain of the 2008 GW crushed RAP rubble material stabilized with cement and/or SS-1 emulsion across low and high stress states. Table 4.13 presents the radial microstrain of the 2008 OGBC crushed RAP rubble material stabilized with cement and/or SS-1 emulsion across low and high stress states.

The unstabilized GW and OGBC RAP specimens had radial microstrain measurements less than the conventional granular base material specimen. Stabilization of the GW and OGBC RAP specimens further reduced the radial microstrain results of these specimens, compared to the unstabilized specimens. The radial microstrain of both the GW and OGBC RAP specimens (unstabilized and cement and/or SS-1 emulsion stabilized) increased from a low stress state to a high stress state. The GW and OGBC RAP specimens showed sensitivity to frequency across all stress states. However, this sensitivity was more pronounced at a high stress state.

Table 4.12 2008 GW RAP Radial Microstrain across Two Stress States

Base Material and Stabilization System	Radial Microstrain			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	185	190	186	181
Unstabilized GW RAP	64	63	75	79
1.0% Cement GW RAP	21	25	31	27
2.0% Cement GW RAP	25	24	26	30
3.0% Cement GW RAP	22	24	27	27
1.0% SS-1 GW RAP	25	27	31	36
2.0% SS-1 GW RAP	17	22	25	26
3.0% SS-1 GW RAP	22	25	32	34
1.0% Cement, SS-1 GW RAP	30	30	32	36
2.0% Cement, SS-1 GW RAP	20	22	27	27
3.0% Cement, SS-1 GW RAP	14	16	22	21
High Stress State				
Conventional COS Granular Base	1815	Failed	Failed	Failed
Unstabilized GW RAP	309	348	429	459
1.0% Cement GW RAP	99	115	141	151
2.0% Cement GW RAP	84	95	118	130
3.0% Cement GW RAP	106	120	148	164
1.0% SS-1 GW RAP	116	138	188	212
2.0% SS-1 GW RAP	81	94	134	159
3.0% SS-1 GW RAP	93	108	150	178
1.0% Cement, SS-1 GW RAP	149	166	211	231
2.0% Cement, SS-1 GW RAP	96	110	142	161
3.0% Cement, SS-1 GW RAP	74	84	112	130

At a low stress state, the OGBC RAP specimens stabilized with cement did not show improvement at a low concentration of one percent cement, relative to the unstabilized OGBC RAP specimens. The cement stabilized OGBC RAP specimens showed improved radial microstrain at concentrations of two and three percent, relative to the unstabilized OGBC RAP specimens. At a low stress state, the SS-1 emulsion stabilized OGBC RAP showed improvement in radial microstrain behavior at a concentration of three percent only, relative to the unstabilized OGBC RAP specimens. At a low stress state, the cement with SS-1 emulsion stabilized RAP showed improvement in radial microstrain behavior at concentrations of one, two and, three percent, relative to the unstabilized OGBC RAP specimens.

Table 4.13 2008 OGBC RAP Radial Microstrain across Two Stress States

Base Material and Stabilization System	Radial Microstrain			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	185	190	186	181
Unstabilized OGBC RAP	26	28	35	39
1.0% Cement OGBC RAP	27	35	39	43
2.0% Cement OGBC RAP	25	23	30	35
3.0% Cement OGBC RAP	19	16	19	21
1.0% SS-1 OGBC RAP	31	33	45	47
2.0% SS-1 OGBC RAP	29	32	40	42
3.0% SS-1 OGBC RAP	15	18	23	26
1.0% Cement, SS-1 OGBC RAP	23	23	27	33
2.0% Cement, SS-1 OGBC RAP	20	20	25	27
3.0% Cement, SS-1 OGBC RAP	22	20	22	24
High Stress State				
Conventional COS Granular Base	1815	Failed	Failed	Failed
Unstabilized OGBC RAP	143	167	228	265
1.0% Cement OGBC RAP	124	145	190	218
2.0% Cement OGBC RAP	105	121	164	184
3.0% Cement OGBC RAP	65	69	96	115
1.0% SS-1 OGBC RAP	129	155	218	258
2.0% SS-1 OGBC RAP	107	129	189	226
3.0% SS-1 OGBC RAP	68	84	122	151
1.0% Cement, SS-1 OGBC RAP	114	128	175	200
2.0% Cement, SS-1 OGBC RAP	97	106	148	174
3.0% Cement, SS-1 OGBC RAP	81	91	133	155

At a high stress state, the OGBC RAP specimens stabilized with cement, SS-1 emulsion, and cement with SS-1 emulsion showed radial microstrain improvement compared to the unstabilized specimens. Radial microstrain values decreased with an increase in stabilizer concentration, from one percent to three percent, across all stabilized specimens, relative to the unstabilized OGBC RAP specimens.

4.7 Chapter Summary

Preliminary laboratory characterization of 2008 crushed reclaimed asphalt pavement (RAP) rubble materials was conducted to establish if conventional laboratory tests were applicable for the RAP materials and to determine stabilizer types and amounts for repeat samples strengthening analysis of 2009 crushed RAP rubble materials.

The impact crushing methodology employed to crush the 2008 GW and OGBC RAP rubble materials resulted in more fractures faces than conventional granular base materials. The asphalt content shows the GW and OGBC RAP have value in terms of overall durability and increased moisture susceptibility as a base course aggregate.

During standard Proctor compaction of the 2008 GW and OGBC RAP materials, the Proctor molds expelled moisture and the RAP materials were visually loosely compacted when removed from the molds. CBR values for the crushed GW RAP and OGBC RAP were unreasonably low.

The frequency sweep testing was limited to one sample of each specimen. Frequency sweep testing showed the viscoelasticity of the RAP materials. OGBC RAP and GW RAP materials, across all RaTT stress states and frequencies, were stiffer than conventional granular base material. The OGBC and GW RAP materials responded well to cement and SS-1 emulsion stabilizers. Stabilizing GW and OGBC RAP materials with cement and/or SS-1 emulsion concentrations of at least two percent improved the overall material properties of the RAP materials. Both unstabilized and stabilized RAP materials showed sensitivity to frequency which was more prominent at an increased deviatoric stress (high stress state). Cement with SS-1 emulsion stabilization improved the performance of SS-1 emulsion stabilized RAP samples. Based on the triaxial frequency sweep RaTT results, the following strengthening systems will be used for further repeat sample analysis of 2009 crushed RAP materials:

- Two percent cement;
- Two percent SS-1 emulsion; and
- One percent cement with one percent SS-1 emulsion.

CHAPTER 5 LABORATORY CHARACTERIZATION OF 2009 CRUSHED RAP MATERIALS

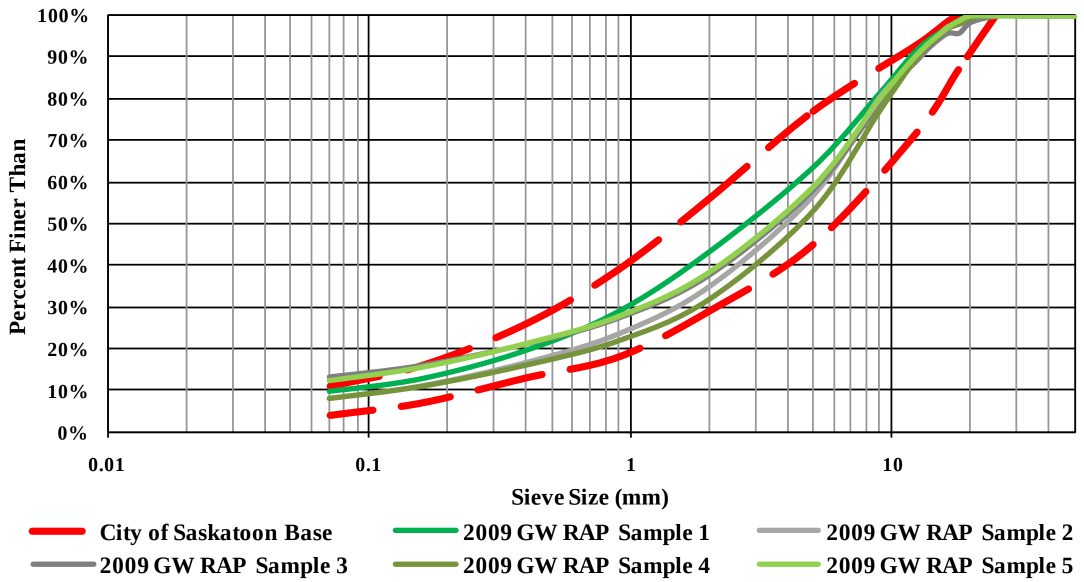
This chapter presents the laboratory characterization results for 2009 crushed reclaimed asphalt pavement (RAP) rubble materials: a well graded (GW) RAP material and an open graded base course (OGBC) RAP material. The 2009 crushed RAP rubble materials were produced using reconfigured impact crushing equipment and material processing techniques. With regards to material processing techniques, protocols were implemented to improve the final crushed RAP product; these protocols included separating the feedstock material by size (large slabs of RAP and smaller pieces) and breaking down large slabs prior to putting them in the impact crusher. With regards to the impact crushing equipment itself, an additional grizzly screen was added to reduced fines and fine material and produced a higher quality RAP material than in 2008 (Berthelot et al. 2010b). Three RAP materials were crushed in 2009: a GW RAP, an OGBC RAP with less fine material, and a RAP rock. (Recall this research is limited to the GW RAP and the OGBC RAP.)

Strengthening systems analyzed in this chapter are 2009 GW and OGBC RAP materials stabilized with two percent cement, two percent SS-1 emulsion, and one percent cement with one percent SS-1 emulsion. Five repeat samples of each system are tested.

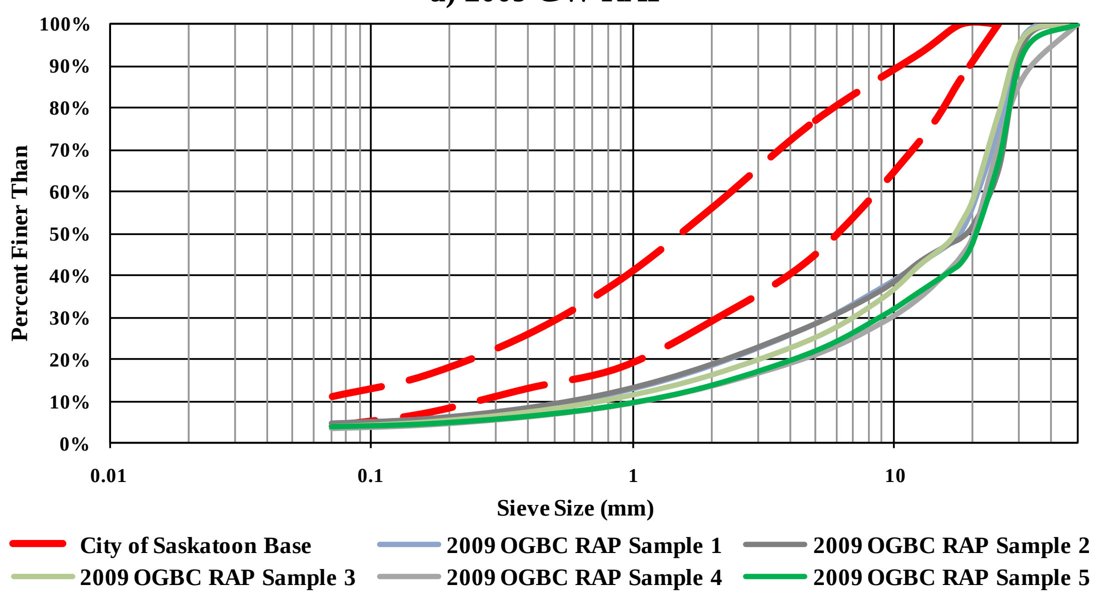
This chapter presents conventional physical property testing results and triaxial frequency sweep analysis results of five repeat samples of each RAP material (GW and OGBC). RAP samples were tested in triaxial frequency sweep following moist curing, then subjected to climatic conditioning using vacuum saturation. Following vacuum saturation, samples were tested again using triaxial frequency sweep testing protocol. Conventional granular base materials were not retested in this chapter as they were characterized in Chapter 4.

5.1 RAP Aggregate Gradations

Five gradations of each type of crushed RAP (GW and OGBC) retrieved from the City of Saskatoon stockpiles were determined in accordance with ASTM C117 and C136 and compared to the City of Saskatoon base aggregate gradation specifications. The gradations are shown in Figure 5.1.



a) 2009 GW RAP



b) 2009 OGBC RAP

Figure 5.1 Gradations of 2009 GW and OGBC RAP

The GW RAP gradations are represented by a smooth particle-distribution line within the COS base aggregate specification limits and the OGBC RAP gradations are coarse of the COS base aggregate bandwidth, with minimal fines. The fines and fine content of the 2009 OGBC RAP was less than that of the 2009 GW RAP and the 2008 OGBC RAP. The 2009 OGBC RAP was crushed to a large, coarse top size of 25 mm with reduced fines and fine sand content. Sample 3 and sample 5 of the GW RAP exceeded the COS upper limits for fines and fine sand content of 12 percent.

5.2 Material Loss on Ignition

Virgin granular base material mass loss on ignition is attributed to organic content and is limited to five percent by weight for COS base aggregates (COS 2005). The mass loss on ignition of crushed RAP materials is attributed to residual asphalt content. Residual asphalt content may be considered of value to aggregate-material performance in terms of overall durability and increased moisture susceptibility.

Table 5.1 lists the material loss on ignition for the 2009 GW and OGBC RAP. The residual asphalt content of the GW RAP ranged from 3.45 percent to 4.21 percent. The residual asphalt content of the OGBC RAP ranged from 5.29 percent to 5.56 percent.

Table 5.1 Material Loss on Ignition for 2009 GW and OGBC RAP

Base Material		Material Loss on Ignition
GW RAP	**Sample 1**	3.5%
	Sample 2	4.2%
	Sample 3	3.7%
	Sample 4	3.6%
	Sample 5	3.5%
OGBC RAP	**Sample 1**	5.5%
	Sample 2	4.8%
	Sample 3	5.6%
	Sample 4	5.5%
	Sample 5	5.3%

Recall that the 2008 OGBC and GW RAP had residual asphalt contents of 5.5 percent and 6.3 percent, respectively. The 2009 OGBC and GW RAP residual asphalt content were less, measuring 3.7 percent and 5.3 percent, respectively. The difference in residual asphalt content between the 2008 and 2009 samples illustrate the stockpile variability of the RAP rubble materials; the difference between the 2008 and 2009 OGBC RAP materials' asphalt content was 1.8 percent and the difference between the 2008 and 2009 GW RAP materials' asphalt content was 1.0 percent.

The OGBC RAP has a higher residual asphalt content compared to the GW RAP because the OGBC RAP was composed of larger particles which were coated with asphalt. This is a result of the impact crushing and screening process. For example, when a large slab of RAP in put in the impact crusher, it will be crushed at the larger top size and screened off in the OGBC RAP stockpile. At the same time, smaller pieces of RAP rubble may be inputted in the impact crusher and will be crushed and screened off in the GW stockpile.

5.3 Mechanistic Climatic Material Properties Characterization

For this set of testing, five repeat samples of GW RAP and OGBC RAP were stabilized with two percent cement, two percent slow-setting (SS-1) emulsion, and one percent cement with one percent SS-1 emulsion. No additional sample(s) of conventional granular base were tested in the RaTT with the 2009 RAP materials. Only the results for the low and high stress states are presented herein for discussion. (Stress states are detailed in Chapter Three.) Complete RaTT results for all stress states are included in Appendix B.

5.3.1 Specimen Preparation

GW and OGBC RAP materials specimens were prepared and compacted in the gyratory compactor at 20°C. Specimens were 150 mm in diameter and 150 ± 5 mm in height. The target density was set equal to the maximum dry density of the GW and OGBC RAP materials under optimum moisture content, as listed in Table 5.2.

Target dry density values for the crushed 2009 RAP rubble materials were determined based on the target dry density value set for the 2008 OGBC RAP, as previously discussed in

Chapter Three. The same target dry density was used for both the GW RAP and OGBC RAP to maintain consistency across compaction parameters.

Table 5.2 Target Dry Density for Gyratory Compaction

Base Material	Maximum Dry Density (kg/m^3)	Optimum Moisture Content
GW RAP	2200	1.9%
OGBC RAP	2200	1.9%

All materials samples were moist cured for a minimum of 28 days in a moist cure room prior to rapid triaxial frequency sweep testing in the rapid triaxial tester (RaTT), conducted at 20°C.

5.3.2 Specimen Failure

If a specimen failed in vacuum saturation, it fell apart by crumbling upon removal from the saturation chamber and post vacuum saturation frequency sweep testing was not possible. Figure 5.2 illustrates two photos (side view and top view) of unstabilized GW RAP samples that failed after vacuum saturation.

A material specimen could also fail at any given RaTT stress state and frequency. If a specimen failed after the last frequency at the low stress state, triaxial frequency sweep testing was complete and the specimen was removed from the RaTT.

During triaxial frequency sweep by RaTT, no 2009 GW and OGBC RAP specimens failed in post moist cure testing. All of the unstabilized GW RAP specimens failed during vacuum saturation (VacSat) testing and were unable to be tested in the RaTT. On average, the two percent SS-1 emulsion stabilized GW RAP VacSat specimens failed at the end of the medium stress state; therefore, high stress state results for these specimens are not presented. None of the OGBC RAP specimens failed during vacuum saturation testing. On average, the two percent SS-1 emulsion stabilized OGBC RAP VacSat specimens failed in the high stress state during the 0.5 Hz frequency sweep.

a) Side View **b) Top View**

Figure 5.2 Typical Unstabilized GW RAP Sample Failure in Vacuum Saturation Testing

5.3.3 Dynamic Modulus Characterization

As explained in Chapter Three, dynamic modulus is a viscoelastic material property representing the ratio of peak axial stress over peak axial strain under sinusoidal loading. Dynamic modulus measures the stiffness of a material under dynamic loading. Dynamic modulus and strain response are inversely proportional, therefore under an applied load a material with a higher stiffness will result in lower strains. Table 5.3, Figure 5.3, and Figure 5.4 illustrate the average dynamic modulus results for the 2009 GW RAP specimens. Figure 5.5, Figure 5.6, and Table 5.4 illustrate the average dynamic modulus results for the 2009 OGBC RAP specimens. Error bars represent maximum and minimum measured dynamic modulus values out of the five repeat samples.

The dynamic modulus decreased as deviatoric stress increased from low to high stress states for both the 2009 GW and OGBC RAP materials. This means the stiffness of the unstabilized and stabilized RAP materials decreased with an increase in applied deviatoric stress. As the frequency decreased from 10 Hz to 0.5 Hz, the magnitude of the dynamic modulus decreased, across all RAP specimens. This illustrates that viscoelastic materials are sensitive to both stress and frequency. The increased sensitivity of the RAP material to load frequency illustrates the viscosity effects of the asphalt cement on its overall material properties. Neither cement and/or emulsion treatment reduced this sensitivity to load frequency. Vacuum saturation (VacSat) conditioning decreased the magnitude of the dynamic modulus for all RAP specimens, compared to optimal moist cure (MC) conditions.

Table 5.3 Dynamic Modulus for 2009 GW RAP

Base Sample and Stabilizer		Low Stress State				High Stress State			
		10 Hz	5.0 Hz	1.0 Hz	0.5 Hz	10 Hz	5.0 Hz	1.0 Hz	0.5 Hz
0% (MC)	Average (MPa)	1526	1485	1336	1289	1213	1154	1016	959
	St.Dev. (MPa)	87	74	47	44	50	46	34	29
	CV	5.7%	5.0%	3.5%	3.4%	4.1%	4.0%	3.3%	3.0%
0% (VacSat)	Average (MPa)	0	0	0	0	0	0	0	0
	St.Dev. (MPa)	0	0	0	0	0	0	0	0
	CV	-	-	-	-	-	-	-	-
2% Cem (MC)	Average (MPa)	2535	2498	2298	2247	2143	2034	1791	1703
	St.Dev. (MPa)	140	199	166	182	149	132	133	125
	CV	5.5%	8.0%	7.2%	8.1%	6.9%	6.5%	7.4%	7.3%
2% Cem (VacSat)	Average (MPa)	1769	1735	1589	1566	1528	1430	1242	1172
	St.Dev. (MPa)	144	126	119	142	119	106	91	85
	CV	8.1%	7.3%	7.5%	9.1%	7.8%	7.4%	7.3%	7.2%
2% SS-1 (MC)	Average (MPa)	1601	1479	1226	1140	1314	1183	947	867
	St.Dev. (MPa)	79	76	59	48	52	52	32	26
	CV	4.9%	5.1%	4.8%	4.2%	4.0%	4.4%	3.4%	3.0%
2% SS-1 (VacSat)	Average (MPa)	666	636	648	637	0	0	0	0
	St.Dev. (MPa)	133	123	188	217	0	0	0	0
	CV	20%	19%	29%	34%	-	-	-	-
2% Cem/SS-1 (MC)	Average (MPa)	1779	1713	1533	1479	1449	1349	1151	1076
	St.Dev. (MPa)	80	65	55	54	83	73	58	52
	CV	4.5%	3.8%	3.6%	3.7%	5.7%	5.4%	5.0%	4.8%
2% Cem/SS-1 (VacSat)	Average (MPa)	1233	1141	983	912	924	845	700	649
	St.Dev. (MPa)	151	125	110	111	41	29	25	27
	CV	12.2%	11.0%	11.2%	12.2%	4.4%	3.4%	3.6%	4.1%

The OGBC RAP has higher magnitudes of dynamic modulus post moist cure and post vacuum saturation compared to the GW RAP. The unstabilized OGBC RAP specimens did not fail in vacuum saturation and subsequent frequency sweep testing, whereas the unstabilized GW RAP specimens failed in vacuum saturation. This may be due to the particle size and gradation of the OGBC RAP; the OGBC RAP has a top size of 25 mm, reduced fines content, and increased fracture faces when compared to the GW RAP. Particle size, gradation, and angularity are important in the compaction of a material, which directly influences moisture susceptibility and stiffness; therefore, the OGBC RAP may have better particle interlock compared to the GW RAP, which resulted in improved stiffness and higher dynamic modulus properties under vacuum saturation. Also, the OGBC RAP had a higher residual asphalt content compared to the GW RAP which may have improved its moisture susceptibility under vacuum saturation.

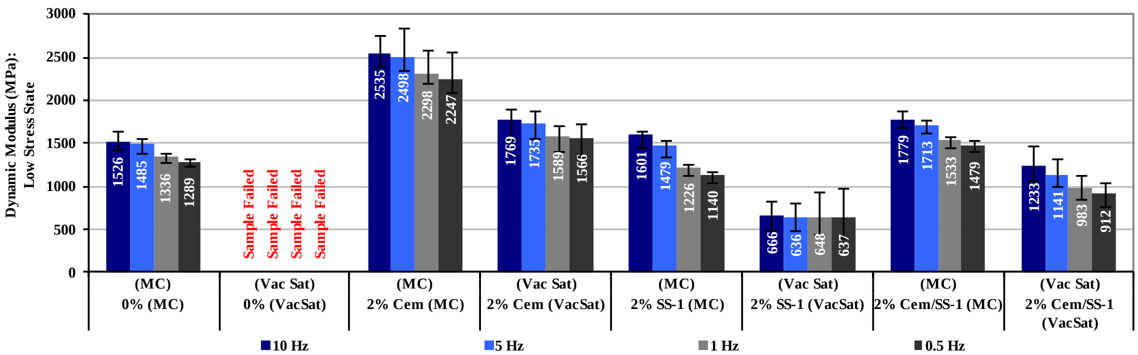


Figure 5.3 Dynamic Modulus across Low Stress State for 2009 GW RAP (±Maximum/Minimum)

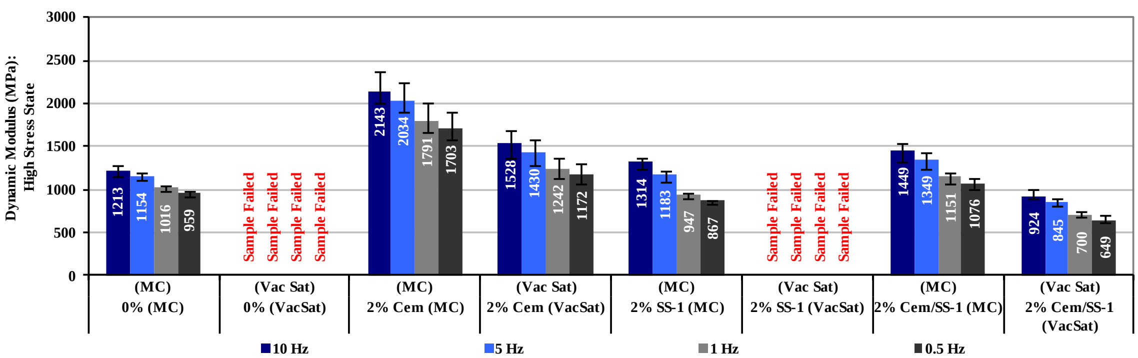


Figure 5.4 Dynamic Modulus across High Stress State for 2009 GW RAP (±Maximum/Minimum)

Cement stabilization increased the stiffness of the GW and OGBC RAP materials and produced dynamic modulus values that were higher than those of the unstabilized RAP. Following climatic vacuum saturation (VacSat) conditioning, the cement stabilized GW RAP specimens retained 70 percent and 69 percent stiffness at the low and high stress states, respectively, across a frequency of 0.5 Hz. Similarly, the cement stabilized OGBC RAP specimens retained 94 percent and 87 percent stiffness at the low and high stress states, respectively, across a frequency of 0.5 Hz. Cement stabilization is known to improve the durability and moisture susceptibility of RAP materials.

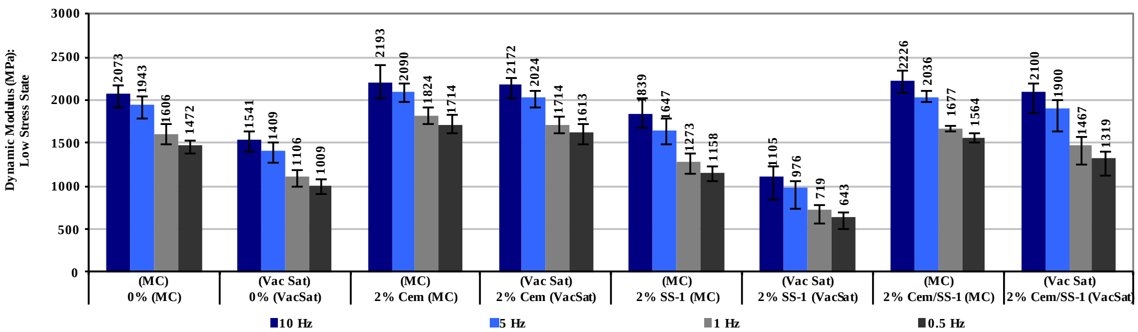


Figure 5.5 Dynamic Modulus across Low Stress State for 2009 OGBC RAP (±Maximum/Minimum)

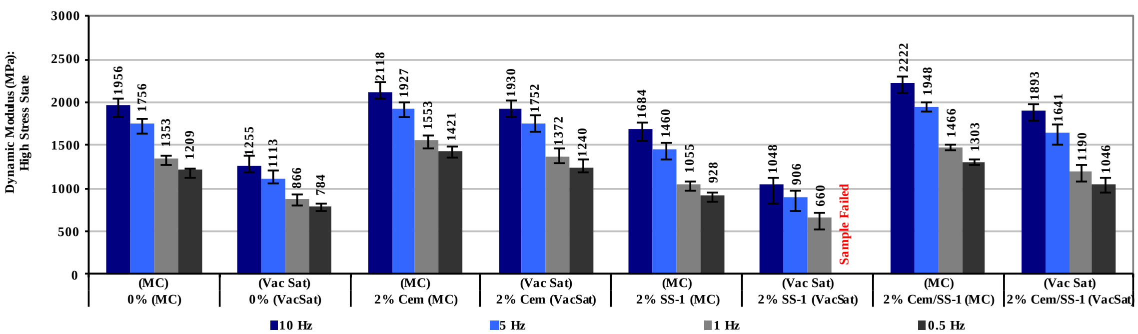


Figure 5.6 Dynamic Modulus across High Stress State for 2009 OGBC RAP (±Maximum/Minimum)

SS-1 emulsion stabilization increased the stiffness of the GW RAP material at a low stress state with a frequency of 10 Hz and at a high stress state with frequencies of 10 Hz and 5.0 Hz, producing dynamic modulus values that were up to eight percent higher than those of the unstabilized GW RAP. SS-1 emulsion stabilization decreased the stiffness of the GW RAP material for the remaining stress state and frequencies, compared to the unstabilized RAP. SS-1 emulsion stabilization decreased the OGBC RAP material and produced dynamic modulus values that were less than those of the unstabilized RAP. Following climatic vacuum saturation (VacSat) conditioning, both the two percent SS-1 emulsion stabilized GW and OGBC RAP specimens retained 56 percent and 0 percent stiffness at the low and high stress states, respectively, across a frequency of 0.5 Hz. Although the SS-1 emulsion improved the moisture susceptibility of the GW RAP materials compared to the unstabilized GW RAP materials in optimal moist cure (MC) conditions, the SS-1 emulsion stabilized GW RAP did not survive vacuum saturation and the SS-1 emulsion stabilized OGBC RAP failed in the high stress state, under a frequency of 0.5 Hz.

Table 5.4 Dynamic Modulus for 2009 OGBC RAP

Base Sample and Stabilizer		Low Stress State				High Stress State			
		10 Hz	**5.0 Hz**	**1.0 Hz**	**0.5 Hz**	**10 Hz**	**5.0 Hz**	**1.0 Hz**	**0.5 Hz**
0% (MC)	**Average (MPa)**	2073	1943	1606	1472	1956	1756	1353	1209
	St.Dev. (MPa)	111	103	93	72	85	70	49	42
	CV	5.4%	5.3%	5.8%	4.9%	4.3%	4.0%	3.6%	3.5%
0% (VacSat)	**Average (MPa)**	1541	1409	1106	1009	1255	1113	866	784
	St.Dev. (MPa)	89	91	66	60	77	64	44	40
	CV	5.8%	6.5%	6.0%	5.9%	6.1%	5.8%	5.1%	5.1%
2% Cem (MC)	**Average (MPa)**	2193	2090	1824	1714	2118	1927	1553	1421
	St.Dev. (MPa)	152	109	92	77	84	71	58	57
	CV	6.9%	5.2%	5.0%	4.5%	4.0%	3.7%	3.7%	4.0%
2% Cem (VacSat)	**Average (MPa)**	2172	2024	1714	1613	1930	1752	1372	1240
	St.Dev. (MPa)	92	81	81	81	74	75	64	60
	CV	4.2%	4.0%	4.7%	5.0%	3.8%	4.3%	4.7%	4.8%
2% SS-1 (MC)	**Average (MPa)**	1839	1647	1273	1158	1684	1460	1055	928
	St.Dev. (MPa)	128	116	81	64	82	73	47	38
	CV	7.0%	7.0%	6.4%	5.5%	4.9%	5.0%	4.5%	4.1%
2% SS-1 (VacSat)	**Average (MPa)**	1105	976	719	643	1048	906	660	0
	St.Dev. (MPa)	149	127	91	80	118	95	71	0
	CV	13.5%	13.0%	12.7%	12.4%	11.3%	10.5%	10.8%	-
2% Cem/SS-1 (MC)	**Average (MPa)**	2226	2036	1677	1564	2222	1948	1466	1303
	St.Dev. (MPa)	90	52	34	43	72	44	30	23
	CV	4.0%	2.6%	2.0%	2.7%	3.2%	2.3%	2.0%	1.8%
2% Cem/SS-1 (VacSat)	**Average (MPa)**	2100	1900	1467	1319	1893	1641	1190	1046
	St.Dev. (MPa)	153	156	130	110	86	89	72	67
	CV	7.3%	8.2%	8.9%	8.3%	4.5%	5.4%	6.1%	6.4%

Cement with SS-1 emulsion stabilization increased the stiffness of the GW and OGBC RAP materials, resulting in dynamic modulus values that were higher than those of the unstabilized RAP and the SS-1 emulsion stabilized RAP. The cement with SS-1 emulsion stabilized RAP materials had improved stiffness compared to the RAP materials stabilized with SS-1 emulsion alone, likely due to the addition of cement which is known to enhance the stiffness of RAP materials. Following climatic vacuum saturation (VacSat) conditioning, GW RAP with two percent cement with SS-1 emulsion retained 62 percent and 60 percent stiffness at the low and high stress states, respectively, across a frequency of 0.5 Hz. Similarly, the two percent cement with SS-1 emulsion retained 84 percent and 80 percent stiffness at the low and high stress states, respectively, across a frequency of 0.5 Hz.

Upon analyzing the coefficient of variances listed in Table 5.3 and Table 5.4, the SS-1 emulsion stabilized GW and OGBC RAP materials post vacuum saturation (VacSat) had the highest variability within the repeat samples. This is likely due to the SS-1 emulsion, which may have caused increased variability under moisture saturation conditioning when dynamic loading is applied.

5.3.4 Poisson's Ratio Characterization

As explained in Chapter Three, Poisson's ratio is a measure of the ratio of radial strain to axial strain, which is a function of the applied load and its frequency. Table 5.5, Figure 5.7, and Figure 5.8 illustrate the Poisson's ratio results for the 2009 GW RAP specimens. Table 5.6, Figure 5.9, and Figure 5.10 illustrate the Poisson's ratio results for the 2009 OGBC RAP specimens. Error bars represent maximum and minimum measured Poisson's ratio values out of the five repeat samples.

The Poisson's ratio increased as deviatoric stress increased from low to high stress states. This means that under higher applied load rates, the RAP materials exhibited higher strains. The magnitude of the Poisson's ratio was greater when load was applied at a frequency of 0.5 Hz, compared to a faster frequency of 10 Hz, across both low and high stress states. This illustrates that viscoelastic materials are sensitive to both stress and frequency.

Table 5.5 Poisson's Ratio for 2009 GW RAP

Base Sample and Stabilizer		Low Stress State				High Stress State			
		10 Hz	**5.0 Hz**	**1.0 Hz**	**0.5 Hz**	**10 Hz**	**5.0 Hz**	**1.0 Hz**	**0.5 Hz**
0% (MC)	**Average**	0.20	0.20	0.21	0.22	0.31	0.33	0.37	0.39
	St.Dev.	0.03	0.02	0.02	0.03	0.03	0.04	0.04	0.03
	CV	15.0%	10.0%	9.5%	13.6%	9.7%	12.1%	10.8%	7.7%
0% (VacSat)	**Average**	0	0	0	0	0	0	0	0
	St.Dev.	0	0	0	0	0	0	0	0
	CV	-	-	-	-	-	-	-	-
2% Cem (MC)	**Average**	0.14	0.14	0.14	0.15	0.20	0.20	0.22	0.23
	St.Dev.	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02
	CV	14.3%	7.1%	7.1%	13.3%	10.0%	10.0%	9.1%	8.7%
2% Cem (VacSat)	**Average**	0.12	0.13	0.14	0.15	0.23	0.23	0.27	0.30
	St.Dev.	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.03
	CV	25.0%	15.4%	21.4%	13.3%	13.0%	8.7%	11.1%	10.0%
2% SS-1 (MC)	**Average**	0.24	0.24	0.26	0.25	0.33	0.34	0.40	0.43
	St.Dev.	0.03	0.02	0.02	0.03	0.02	0.02	0.01	0.01
	CV	12.5%	8.3%	7.7%	12.1%	6.1%	5.9%	2.5%	2.3%
2% SS-1 (VacSat)	**Average**	0.39	0.39	0.48	0.48	0	0	0	0
	St.Dev.	0.07	0.08	0.22	0.20	0	0	0	0
	CV	17.9%	20.5%	45.8%	41.7%	-	-	-	-
2% Cem/SS-1 (MC)	**Average**	0.16	0.15	0.18	0.17	0.28	0.29	0.33	0.35
	St.Dev.	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.05
	CV	25.0%	26.7%	27.8%	23.5%	14.3%	13.8%	12.1%	14.3%
2% Cem/SS-1 (VacSat)	**Average**	0.24	0.25	0.25	0.26	0.45	0.47	0.52	0.55
	St.Dev.	0.08	0.08	0.08	0.07	0.09	0.08	0.06	0.05
	CV	33.3%	32.0%	32.0%	26.9%	20.0%	17.0%	11.5%	9.1%

The GW and OGBC RAP exhibited sensitivity to frequency at slow frequencies of 1.0 Hz and 0.5 Hz. Both the GW and OGBC RAP materials stabilized with two percent cement and two percent SS-1 emulsion reported the same average values of Poisson's ratio at the low stress state for high frequencies of 10 Hz and 5.0 Hz. At slower frequencies, the Poisson's ratio of the RAP stabilized specimens increased, with the exception of the cement stabilized GW RAP at a low stress state and a load frequency of 1.0 Hz, which had the same Poisson's ratio as frequencies of 10 Hz and 5.0 Hz. Higher magnitudes of Poisson's ratio were observed at the high stress state and low frequencies of 1.0 Hz and 0.5 Hz; this loading state would be comparable to a heavy truck load being applied at slow speeds in the field.

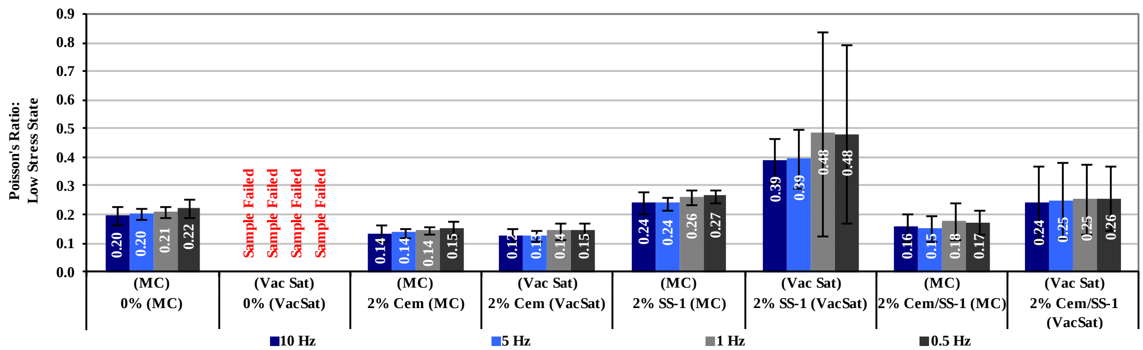


Figure 5.7 Poisson's Ratio across Low Stress State for 2009 GW RAP (±Maximum/Minimum)

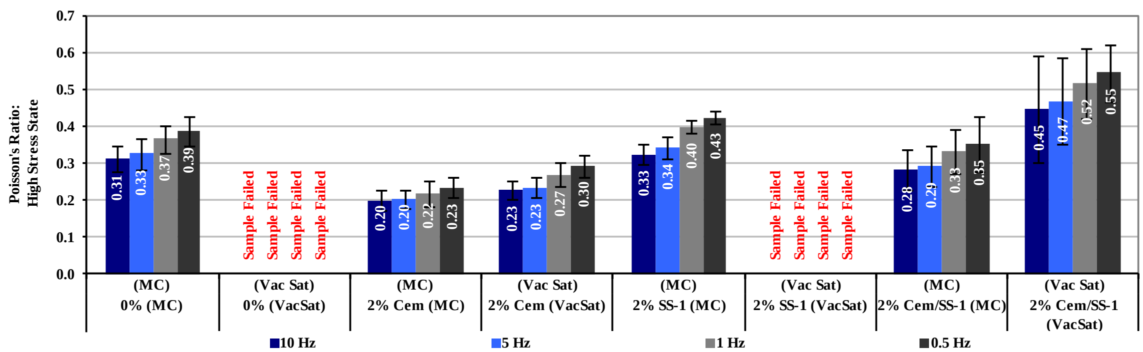


Figure 5.8 Poisson's Ratio across High Stress State for 2009 GW RAP (±Maximum/Minimum)

As reported in Chapter Three, Poisson's ratio values for conventional granular base under the low applied stress state ranged from 0.45 to 0.47 across frequencies. Asphalt concrete has a Poisson's ratio in the order of 0.35 when loaded at high frequencies (Anthony 2008). Moist cured GW and OGBC RAP materials, unstabilized and cement and/or SS-1 emulsion stabilized, had Poisson's ratios lower in magnitude compared to conventional granular base. This may be due to the cohesion effects of the residual asphalt cement; increased cohesion may reduce the radial and lateral strains in the RAP specimens.

Table 5.6 Poisson's Ratio for 2009 OGBC RAP

Base Sample and Stabilizer		Low Stress State				High Stress State			
		10 Hz	5.0 Hz	1.0 Hz	0.5 Hz	10 Hz	5.0 Hz	1.0 Hz	0.5 Hz
0% (MC)	**Average**	0.19	0.21	0.22	0.23	0.25	0.26	0.30	0.33
	St.Dev.	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02
	CV	10.5%	9.5%	9.1%	8.7%	8.0%	7.7%	3.3%	6.1%
0% (VacSat)	**Average**	0.28	0.28	0.29	0.31	0.43	0.44	0.47	0.49
	St.Dev.	0.03	0.02	0.03	0.02	0.03	0.04	0.04	0.03
	CV	10.7%	7.1%	10.3%	6.5%	7.0%	9.1%	8.5%	6.1%
2% Cem (MC)	**Average**	0.14	0.15	0.18	0.18	0.21	0.22	0.26	0.28
	St.Dev.	0.04	0.02	0.04	0.04	0.04	0.04	0.05	0.04
	CV	28.6%	13.3%	22.2%	22.2%	19.0%	18.2%	19.2%	14.3%
2% Cem (VacSat)	**Average**	0.19	0.20	0.22	0.23	0.24	0.26	0.29	0.32
	St.Dev.	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.03
	CV	10.5%	15.0%	13.6%	13.0%	8.3%	11.5%	10.3%	9.4%
2% SS-1 (MC)	**Average**	0.25	0.25	0.28	0.28	0.33	0.35	0.40	0.43
	St.Dev.	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02
	CV	8.0%	8.0%	3.6%	7.1%	6.1%	5.7%	5.0%	4.7%
2% SS-1 (VacSat)	**Average**	0.42	0.42	0.47	0.48	0.54	0.58	0.65	0.00
	St.Dev.	0.05	0.05	0.06	0.06	0.06	0.07	0.08	0.00
	CV	11.9%	11.9%	12.8%	12.5%	11.1%	12.1%	12.3%	-
2% Cem/SS-1 (MC)	**Average**	0.20	0.22	0.25	0.25	0.27	0.28	0.32	0.35
	St.Dev.	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.02
	CV	5.0%	9.1%	4.0%	8.0%	3.7%	3.6%	3.1%	5.7%
2% Cem/SS-1 (VacSat)	**Average**	0.25	0.27	0.31	0.30	0.32	0.33	0.38	0.42
	St.Dev.	0.02	0.02	0.05	0.02	0.03	0.03	0.03	0.03
	CV	8.0%	7.4%	16.1%	6.7%	9.4%	9.1%	7.9%	7.1%

The GW RAP materials failed in vacuum saturation conditioning. The cement stabilized GW RAP materials had reduced Poisson's ratio values post vacuum saturation (VacSat) and post moist cure (MC), compared to the unstabilized GW RAP material in optimal moist cure conditions. The OGBC RAP materials did not fail in vacuum saturation, however the cement stabilized OGBC materials followed the same trend as the cement stabilized GW RAP materials post vacuum saturation (VacSat) and post moist cure (MC), compared to the unstabilized OGBC RAP material in optimal moist cure conditions. In addition, the OGBC RAP materials stabilized with two percent cement had approximately the same Poisson's ratio magnitudes as the unstabilized OGBC RAP materials, showing that under moisture saturated conditions, the cement stabilized OGBC RAP will perform as well as the unstabilized OGBC RAP under optimal MC conditions. Cement stabilization improves the moisture susceptibility of the RAP materials.

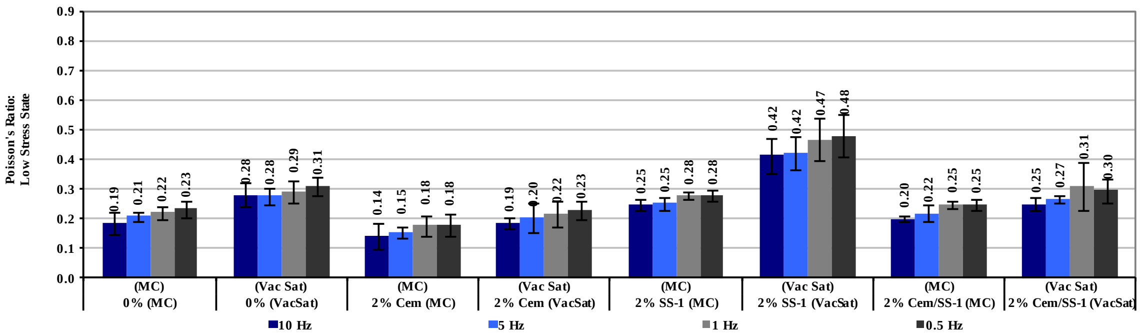


Figure 5.9 Poisson's Ratio across Low Stress State for 2009 OGBC RAP (±Maximum/Minimum)

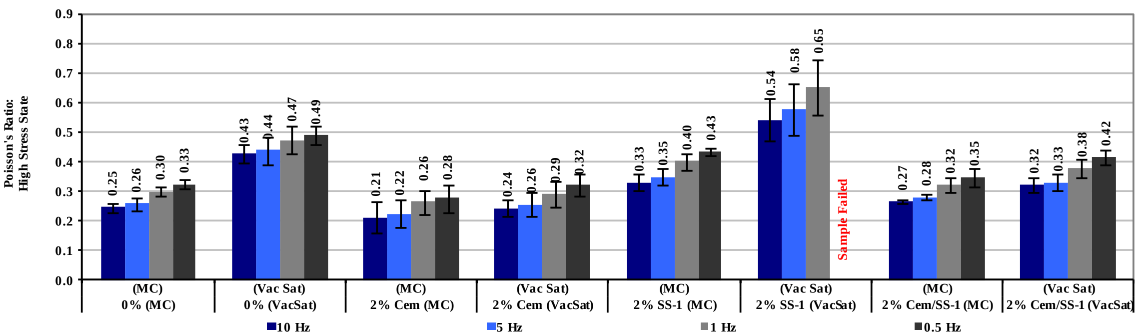


Figure 5.10 Poisson's Ratio across High Stress State for 2009 OGBC RAP (±Maximum/Minimum)

The GW RAP were less sensitivity to frequency compared to the OGBC RAP, which demonstrated more sensitivity to frequency and a general trend of increasing magnitude of Poisson's ratio with decreasing frequency. This may be due to the higher residual asphalt content of the OGBC RAP compared to the GW RAP.

SS-1 emulsion stabilization resulted in increased magnitudes of Poisson ratios across both RAP types, deviatoric loadings and frequencies, and conditioning states, compared to unstabilized RAP and cement stabilized RAP. Although SS-1 emulsion improved the moisture susceptibility of the GW RAP materials compared to the unstabilized GW RAP materials (which did not survive vacuum saturation), the magnitude of the Poisson's ratio for the vacuum saturated GW RAP stabilized with SS-1 emulsion increased significantly, compared to optimal moist cure conditions (MC). The same trend was observed for cement with SS-1 emulsion stabilized GW and OGBC RAP. It seems the SS-1 emulsion did not improve the moisture susceptibility of the RAP as much as the cement stabilization alone. The high deviatoric stress state may have caused de-densification of SS-1 stabilized GW and OGBC RAP, which induces higher radial strains and results in increased Poisson's ratio values.

Under vacuum saturated (VacSat) conditions, the cement with SS-1 stabilized GW RAP and the SS-1 stabilized OGBC RAP had magnitudes of Poisson's ratios nearing or exceeding 0.5. This is likely due to the increased moisture in the testing specimens because moisture in a base layer can increase its viscoelastic behavior, especially when the Poisson's ratio values are greater than 0.50.

5.3.5 Phase Angle Characterization

As explained in Chapter Three, phase angle can be used to indicate the viscoelastic properties of a material. In a repeated sinusoidal load test, phase angle is measured as the time shift between the applied stress and the resultant strain. Table 5.7, Figure 5.11, and Figure 5.12 illustrate the phase angle results for the 2009 GW RAP specimens. Table 5.8, Figure 5.13, and Figure 5.14 illustrate the phase angle results for the 2009 OGBC RAP specimens. Error bars represent maximum and minimum measured Poisson's ratio values out of the five repeat samples.

The phase angle increased as deviatoric stress increased from low to high stress states for both the GW and OGBC RAP materials. This means that a higher deviatoric stress state increased the viscoelastic material properties of the RAP materials. The phase angle decreased as frequency was reduced from 10.0 Hz to 0.5 Hz. A decrease in phase angle can be evidence of an increase in elastic properties and a decrease in viscous properties.

The average phase angle of all stabilization systems for the OGBC RAP was greater at the high stress state compared to the low stress state (with the exception of vacuum saturated SS-1 emulsion stabilized OGBC RAP specimens which failed, on average, in the high stress state).

This is indicative that a high stress state increases the viscous properties and consequently, the viscoelastic behavior of the OGBC RAP materials.

Table 5.7 Phase Angle for 2009 GW RAP

Base Sample and Stabilizer		Low Stress State				High Stress State			
		10 Hz	5.0 Hz	1.0 Hz	0.5 Hz	10 Hz	5.0 Hz	1.0 Hz	0.5 Hz
0% (MC)	Average (deg.)	13.4	12.3	11.3	11.5	15.5	14.3	13.9	13.8
	St.Dev. (deg.)	0.6	0.9	0.9	0.5	0.3	0.4	0.3	0.3
	CV	4.5%	7.3%	8.0%	4.3%	1.9%	2.8%	2.2%	2.2%
0% (VacSat)	Average (deg.)	0	0	0	0	0	0	0	0
	St.Dev. (deg.)	0	0	0	0	0	0	0	0
	CV	-	-	-	-	-	-	-	-
2% Cem (MC)	Average (deg.)	11.2	10.0	9.2	9.9	13.1	12.2	11.9	12.0
	St.Dev. (deg.)	0.8	0.8	0.3	0.2	0.6	0.5	0.2	0.3
	CV	7.1%	8.0%	3.3%	2.0%	4.6%	4.1%	1.7%	2.5%
2% Cem (VacSat)	Average (deg.)	14.4	12.9	11.9	11.7	16.4	14.7	13.9	13.6
	St.Dev. (deg.)	0.7	0.5	0.5	0.5	0.4	0.3	0.4	0.2
	CV	4.9%	3.9%	4.2%	4.3%	2.4%	2.0%	2.9%	1.5%
2% SS-1 (MC)	Average (deg.)	18.4	17.1	15.7	15.3	21.4	19.9	18.6	17.9
	St.Dev. (deg.)	0.4	0.3	0.1	0.4	0.2	0.1	0.2	0.2
	CV	2.2%	1.8%	0.6%	2.6%	0.9%	0.5%	1.1%	1.1%
2% SS-1 (VacSat)	Average (deg.)	22.0	19.5	16.8	13.4	0	0	0	0
	St.Dev. (deg.)	1.0	0.9	0.9	4.2	0	0	0	0
	CV	4.5%	4.6%	5.4%	31.3%	-	-	-	-
2% Cem/SS-1 (MC)	Average (deg.)	14.1	13.2	12.4	11.8	17.1	15.9	15.0	15.1
	St.Dev. (deg.)	1.0	0.1	0.7	0.6	0.5	0.5	0.5	0.4
	CV	6.8%	4.4%	6.0%	4.8%	2.9%	3.1%	3.3%	2.6%
2% Cem/SS-1 (VacSat)	Average (deg.)	18.1	16.3	14.3	14.0	20.6	18.9	17.2	16.8
	St.Dev. (deg.)	0.6	0.8	0.7	0.6	0.6	0.4	0.3	0.2
	CV	3.3%	4.9%	4.9%	4.3%	2.9%	2.1%	1.7%	1.2%

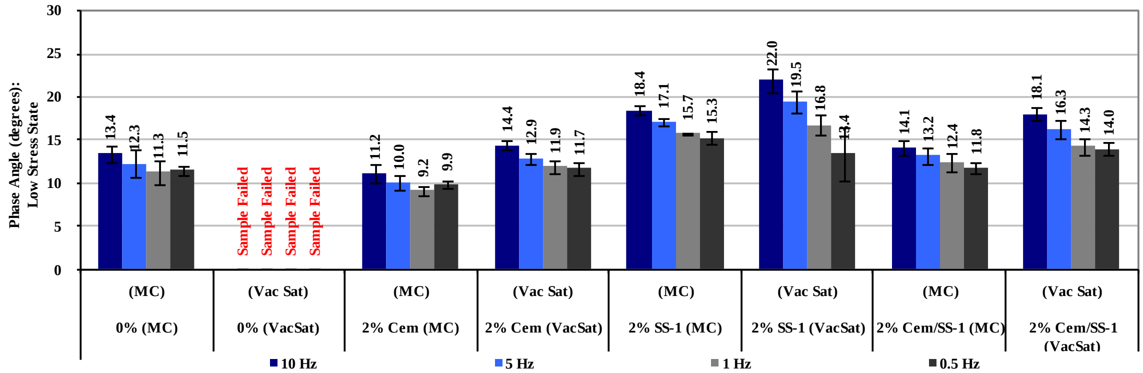


Figure 5.11 Phase Angle across Low Stress State for 2009 GW RAP (±Maximum/Minimum)

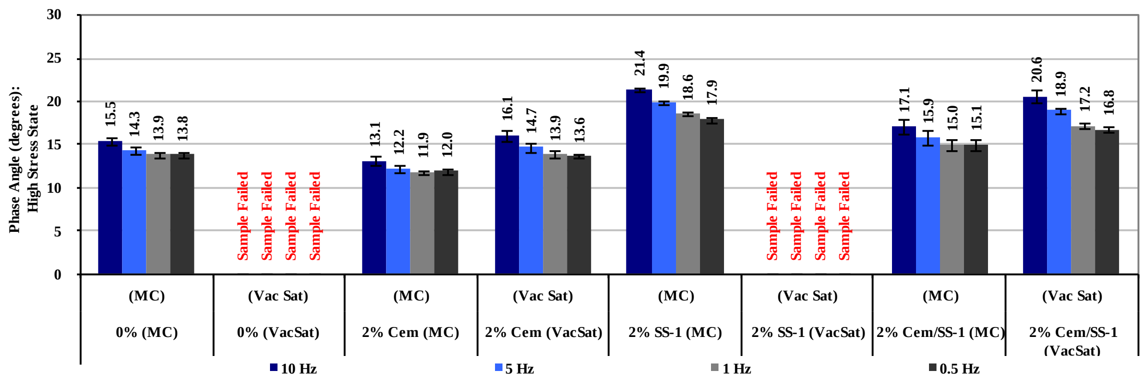


Figure 5.12 Phase Angle across High Stress State for 2009 GW RAP (±Maximum/Minimum)

The two percent SS-1 emulsion treated OGBC RAP and GW RAP materials exhibited the highest phase angle when compared to the phase angles of other stabilization systems. Comparing the OGBC RAP and GW RAP stabilized with SS-1, the magnitude of the phase angle measured for the OGBC RAP with SS-1 is greater that the phase angles measure for the GW RAP with SS-1. Recall that the Poisson's ratio values of the SS-1 stabilized OGBC and GW RAP were very similar; however the OGBC RAP was stiffer than the GW RAP when stabilized with SS-1 emulsion. The phase angle magnitudes illustrate that stabilizing RAP with SS-1 emulsion results in a more viscoelastic material than when stabilizing RAP with cement.

Table 5.8 Phase Angle across for 2009 OGBC RAP

Base Sample and Stabilizer		Low Stress State				High Stress State			
		10 Hz	**5.0 Hz**	**1.0 Hz**	**0.5 Hz**	**10 Hz**	**5.0 Hz**	**1.0 Hz**	**0.5 Hz**
0% (MC)	**Average (deg.)**	17.7	17.0	16.9	16.9	19.6	18.5	18.7	18.7
	St.Dev. (deg.)	0.5	0.5	0.3	0.6	0.4	0.4	0.2	0.3
	CV	2.8%	2.9%	1.8%	3.6%	2.0%	2.2%	1.1%	1.6%
0% (VacSat)	**Average (deg.)**	21.5	20.0	18.0	17.5	21.7	20.1	18.8	18.3
	St.Dev. (deg.)	0.6	0.3	0.5	0.3	0.4	0.5	0.4	0.4
	CV	2.8%	1.5%	2.8%	1.7%	1.8%	2.5%	2.1%	2.2%
2% Cem (MC)	**Average (deg.)**	14.7	14.1	14.0	14.3	17.2	16.4	16.6	16.8
	St.Dev. (deg.)	1.1	0.7	0.7	1.0	0.5	0.5	0.5	0.2
	CV	7.5%	5.0%	5.0%	7.0%	2.9%	3.0%	3.0%	1.2%
2% Cem (VacSat)	**Average (deg.)**	17.6	16.1	15.6	15.6	19.0	18.2	17.6	17.5
	St.Dev. (deg.)	0.5	0.5	0.7	0.7	0.6	0.4	0.3	0.4
	CV	2.8%	3.1%	4.5%	4.5%	3.2%	2.2%	1.7%	2.3%
2% SS-1 (MC)	**Average (deg.)**	22.6	21.5	20.3	19.2	24.7	23.2	21.8	21.3
	St.Dev. (deg.)	0.7	0.4	0.5	0.6	0.4	0.3	0.4	0.3
	CV	3.1%	1.9%	2.5%	3.1%	1.6%	1.3%	1.8%	1.4%
2% SS-1 (VacSat)	**Average (deg.)**	27.0	24.9	22.3	21.1	24.3	22.5	21.9	0.0
	St.Dev. (deg.)	0.9	0.9	0.6	0.7	0.3	0.3	0.3	0.0
	CV	3.3%	3.6%	2.7%	3.3%	1.2%	1.3%	1.4%	-
2% Cem/SS-1 (MC)	**Average (deg.)**	18.9	17.9	17.7	17.1	21.0	20.0	19.9	19.9
	St.Dev. (deg.)	1.4	1.2	0.6	0.6	0.6	0.5	0.2	0.3
	CV	7.4%	6.7%	3.4%	3.5%	2.9%	2.5%	1.0%	1.5%
2% Cem/SS-1 (VacSat)	**Average (deg.)**	21.7	20.4	19.4	18.8	23.1	21.8	20.7	20.2
	St.Dev. (deg.)	1.0	1.0	0.8	1.0	0.9	0.6	0.7	0.6
	CV	4.6%	4.9%	4.1%	5.3%	3.9%	2.8%	3.4%	3.0%

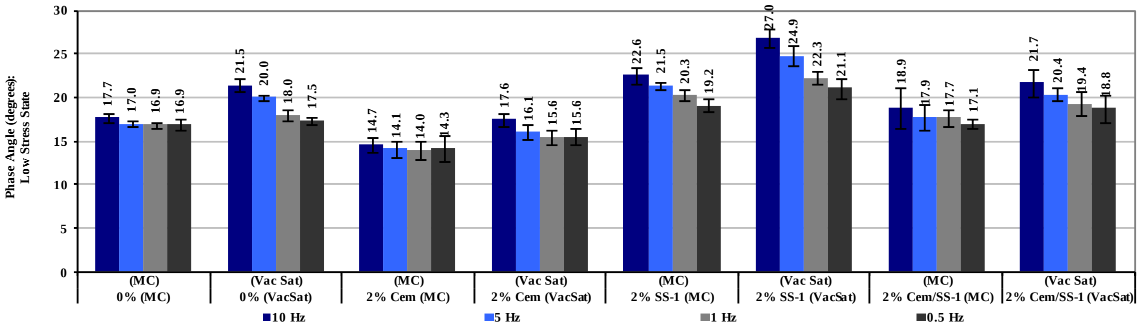


Figure 5.13 Phase Angle across Low Stress State for 2009 OGBC RAP (±Maximum/Minimum)

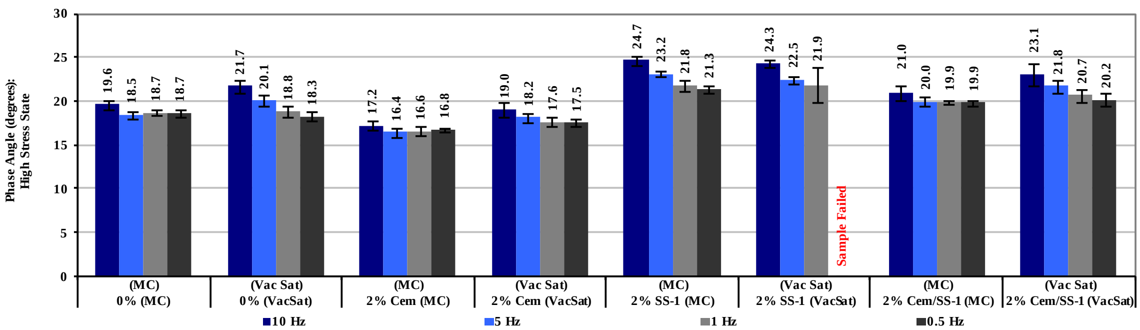


Figure 5.14 Phase Angle across High Stress State for 2009 OGBC RAP (±Maximum/Minimum)

5.3.6 Radial Microstrain Characterization

As explained in Chapter Three, radial microstrain provides an indication of the potential of a material to fail in shear and is also considered to indicate a material's resilience to edge shear failure. Table 5.9, Figure 5.15, and Figure 5.16 illustrate the radial microstrain results for the 2009 GW RAP specimens. Table 5.10, Figure 5.17, and Figure 5.18 illustrate the radial microstrain results for the 2009 OGBC RAP specimens. Error bars represent maximum and minimum measured Poisson's ratio values out of the five repeat samples.

The radial microstrain increased as deviatoric stress increased from low to high stress states. The magnitude of the radial microstrain measured at 0.5 Hz was greater than the radial microstrain measured at 10 Hz. The highest radial microstrains were measured under a high deviatoric stress state and at a low frequency. This loading state represents a heavy truck moving at a very low traffic speed.

Table 5.9 Radial Microstrain for 2009 GW RAP

Base Sample and Stabilizer		Low Stress State				High Stress State			
		10 Hz	5.0 Hz	1.0 Hz	0.5 Hz	10 Hz	5.0 Hz	1.0 Hz	0.5 Hz
0% (MC)	Average	25	27	32	35	138	154	198	222
	St.Dev.	4	4	3	6	20	23	26	26
	CV	16.0%	14.8%	9.4%	17.1%	14.5%	14.9%	13.1%	11.7%
0% (VacSat)	Average	0	0	0	0	0	0	0	0
	St.Dev.	0	0	0	0	0	0	0	0
	CV	-	-	-	-	-	-	-	-
2% Cem (MC)	Average	11	11	12	13	50	54	67	76
	St.Dev.	2	1	1	2	5	6	7	6
	CV	18.2%	9.1%	8.3%	15.4%	10.0%	11.1%	10.4%	7.9%
2% Cem (VacSat)	Average	14	15	18	19	81	89	120	139
	St.Dev.	4	3	5	4	14	14	20	22
	CV	28.6%	20.0%	27.8%	21.1%	17.3%	15.7%	16.7%	15.8%
2% SS-1 (MC)	Average	30	32	42	46	132	157	231	269
	St.Dev.	3	2	3	3	5	6	4	6
	CV	10.0%	6.3%	7.1%	6.5%	3.8%	3.8%	1.7%	2.2%
2% SS-1 (VacSat)	Average	122	129	150	156	0	0	0	0
	St.Dev.	46	48	60	70	0	0	0	0
	CV	37.7%	37.2%	40.0%	44.9%	-	-	-	-
2% Cem/SS-1 (MC)	Average	17	17	23	23	104	118	159	180
	St.Dev.	5	5	6	5	16	17	22	27
	CV	29.4%	29.4%	26.1%	21.7%	15.4%	14.4%	13.8%	15.0%
2% Cem/SS-1 (VacSat)	Average	38	43	51	56	250	300	405	460
	St.Dev.	10	11	14	15	40	39	36	29
	CV	26.3%	25.6%	27.5%	26.8%	16.0%	13.0%	8.9%	6.3%

Both GW and OGBC RAP materials were more sensitive to frequency at a high stress state, compared to the low stress state. This indicates that under a heavier load, RAP materials may expand radially under traffic loads in the field, reducing resilience to edge shear failure.

Unstabilized GW RAP materials had higher magnitudes of radial microstrain compared to the unstabilized OGBC RAP materials. This may be due to the particle interlock of the OGBC RAP, which has more fracture faces, less fines, and a higher particle top size than the GW RAP. In addition, the OGBC RAP materials stabilized with two percent cement and cement with SS-1 emulsion had approximately the same radial microstrain magnitudes as the unstabilized OGBC RAP materials, showing that under moisture saturated conditions, OGBC RAP stabilized with cement with or without SS-1 will perform as well as the unstabilized OGBC RAP under optimal MC conditions SS-1 emulsion stabilized GW and OGBC RAP materials had an increase in magnitude of radial microstrain compared to the unstabilized GW RAP material, under moist cure conditions. Cement stabilization improved the GW RAP material's radial microstrain behavior, whereas the SS-1 emulsion stabilization did not.

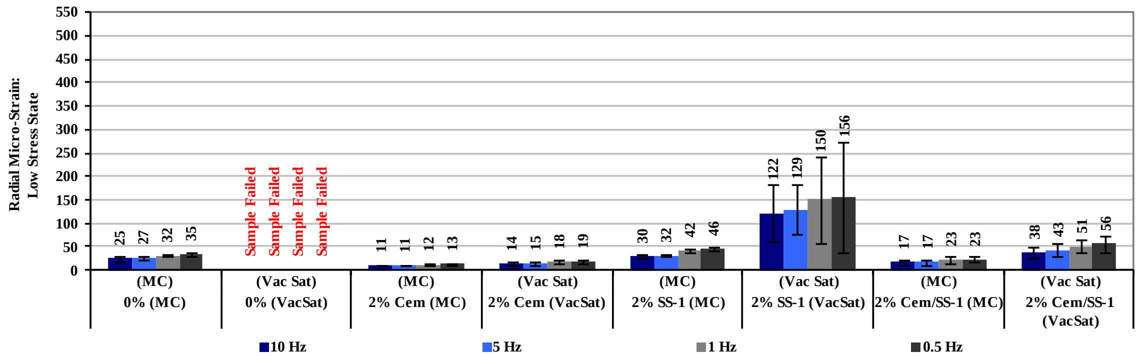


Figure 5.15 Radial Microstrain across Low Stress State for 2009 GW RAP (±Maximum/Minimum)

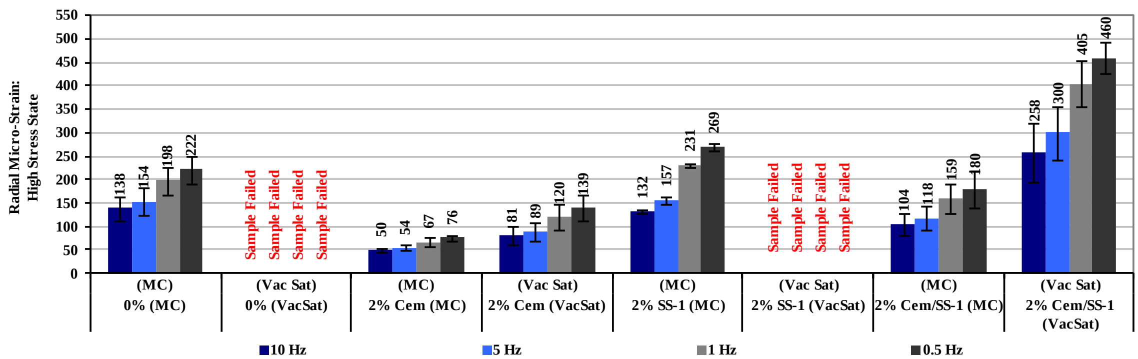


Figure 5.16 Radial Microstrain across High Stress State for 2009 GW RAP (±Maximum/Minimum)

Table 5.10 Radial Microstrain for 2009 OGBC RAP

Base Sample and Stabilizer		Low Stress State				High Stress State			
		10 Hz	5.0 Hz	1.0 Hz	0.5 Hz	10 Hz	5.0 Hz	1.0 Hz	0.5 Hz
0% (MC)	Average	18	21	27	31	68	80	122	147
	St.Dev.	2	1	1	3	2	4	5	7
	CV	11.1%	4.8%	3.7%	9.7%	2.9%	5.0%	4.1%	4.8%
0% (VacSat)	Average	36	39	53	61	182	215	300	342
	St.Dev.	6	5	8	8	21	27	31	30
	CV	16.7%	12.8%	15.1%	13.1%	11.5%	12.6%	10.3%	8.8%
2% Cem (MC)	Average	15	15	21	23	54	63	94	111
	St.Dev.	1	1	2	2	9	9	14	13
	CV	6.7%	6.7%	9.5%	8.7%	16.7%	14.3%	14.9%	11.7%
2% Cem (VacSat)	Average	17	20	25	28	67	80	117	142
	St.Dev.	2	3	4	4	6	10	16	18
	CV	11.8%	15.0%	16.0%	14.3%	9.0%	12.5%	13.7%	12.7%
2% SS-1 (MC)	Average	26	30	43	47	105	130	210	257
	St.Dev.	3	3	3	4	8	10	16	17
	CV	11.5%	10.0%	7.0%	8.5%	7.6%	7.7%	7.6%	6.6%
2% SS-1 (VacSat)	Average	76	88	133	151	283	353	552	0
	St.Dev.	2	23	36	39	66	83	117	0
	CV	2.6%	26.1%	27.1%	25.8%	23.3%	23.5%	21.2%	-
2% Cem/SS-1 (MC)	Average	18	21	30	31	64	78	121	146
	St.Dev.	1	2	1	1	3	3	6	9
	CV	5.6%	9.5%	3.3%	3.2%	4.7%	3.8%	5.0%	6.2%
2% Cem/SS-1 (VacSat)	Average	23	28	40	44	91	110	176	219
	St.Dev.	3	4	5	5	12	14	21	27
	CV	13.0%	14.3%	12.5%	11.4%	13.2%	12.7%	11.9%	12.3%

Vacuum saturated GW RAP specimens stabilized with two percent SS-1 emulsion had a larger range of radial microstrain measurements than the other stabilized vacuum saturated specimens, illustrated in Figure 5.15 and Figure 5.16 by error bars that represent maximum and minimum radial microstrain values for the five repeat samples, across each frequency sweep. The SS-1 emulsion stabilized GW RAP had the highest increase in radial microstrain following vacuum saturation, compared to cement and cement with SS-1 emulsion stabilized specimens. The variability of the radial microstrain measurements increased with post vacuum saturation testing. For example, the GW RAP specimens stabilized with two percent SS-1 emulsion had an average coefficient of variation of 40 percent at a low stress state. Cement and cement with SS-1 emulsion stabilized GW RAP had an average coefficient of variation of 24 percent and 27 percent, respectively, at a low stress state. This may be due to the effect of moisture within the aggregate structure of the RAP specimens, which can increase the variability in response to axial loading.

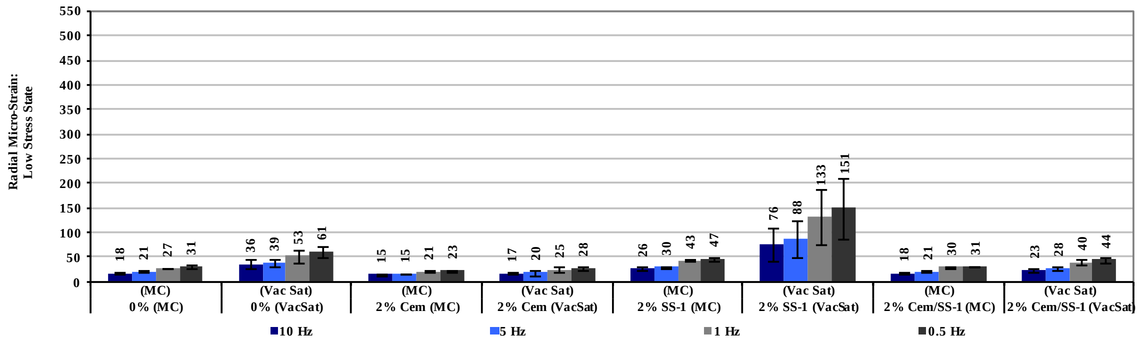


Figure 5.17 Radial Microstrain across Low Stress State for 2009 OGBC RAP

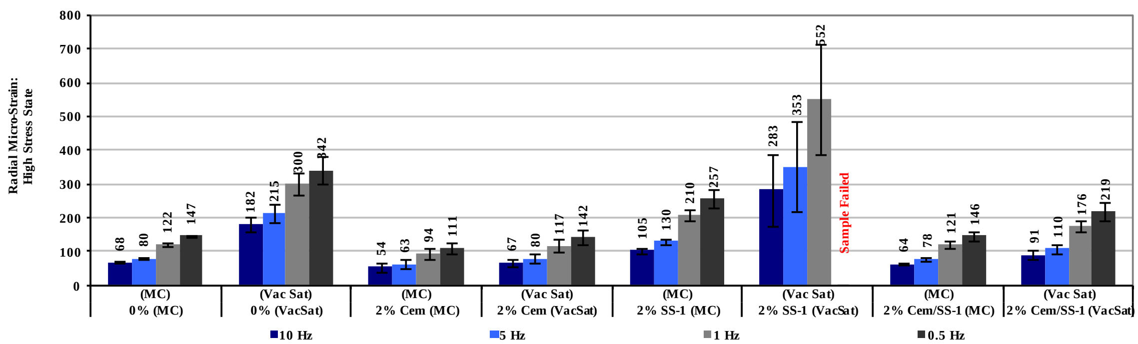


Figure 5.18 Radial Microstrain across High Stress State for 2009 OGBC RAP

5.4 City of Saskatoon Field Application

In 2009 the City of Saskatoon implemented the Green Streets Infrastructure Program and used impact crushed reclaimed asphalt pavement (RAP) materials as base layers in 18,000 m^2 of test section test sections. City engineers worked with consultants and contractors to crush and recycle RAP and Portland cement concrete and use these materials in the rehabilitation of Green Street roadway test sections. The test sections chosen by City engineers were known to have drainage issues and structural failures. To demonstrate the applicability of the RAP materials used in this research, a brief summary of two roads rehabilitated under the Green Streets

Program by the City of Saskatoon is included here, with additional information provided in Appendix C.

Test sections of Marquis Drive and 8th Street East were rehabilitated with RAP base layers stabilized with two percent SS-1 emulsion and one percent cement with one percent SS-1 emulsion, respectively. Both test sections included PCC drainage layers and hot mix asphalt concrete (HMAC) surfacing. Geosynthetics and weeping tile were used to separate subgrade and drainage layer, as well as the drainage layer and the RAP base layer. Traditional construction equipment was used for the reconstruction of the test sections. No specialized equipment was used for hauling, placement, or compaction.

Falling weight deflectometer peak surface deflection measurements were taken pre and post construction for both test sections. Pre construction, average peak surface deflections were greater than COS recommended maximum deflection of 0.75 mm and varied across the length and width of the road for both test sections. Post construction, the average deflections were reduced to 0.44 mm and 0.28 mm for 8th Street and Marquis Drive, respectively. Overall, the west and east end Marquis Drive peak deflections reduced by 70 percent and 71 percent, respectively.

With regards to the economic implications of using crushed RAP materials as a base aggregate in a City of Saskatoon road structure in lieu of virgin granular base material, the capital costs of virgin granular base were greater due to the increased haul required to transport granular base materials in from pits located outside the city limits. The test section base layers constructed with RAP material cost approximately 48 percent to 65 percent less than conventional virgin base material counterparts, demonstrating that using RAP as a base layer is economically feasible.

5.5 Chapter Summary

The 2009 well graded (GW) and open graded base course (OGBC) materials met City of Saskatoon granular base physical material property specification. The residual asphalt content of the 2009 OGBC and GW averaged 3.7 percent and 5.3 percent, respectively. The difference in residual asphalt content between the 2008 and 2009 samples illustrates the stockpile variability of the RAP rubble materials and is likely a result of the reconfigured impact crushing equipment used in 2009 (Berthelot et al. 2010b).

Viscoelastic material behavior was observed in triaxial frequency sweep analysis measured RAP material properties. The magnitude of the dynamic modulus decreased as the load frequency decreased from 10 Hz to 0.5 Hz and increased with an increase in deviatoric stress state, across all RAP specimens, illustrating that viscoelastic materials are sensitive to both stress and frequency. RAP materials exhibited higher strains under higher load rates; the Poisson's ratio increased as deviatoric stress increased from low to high stress states. Also, the magnitude of the Poisson's ratio was greater when load was applied at a frequency of 0.5 Hz, compared to a faster frequency of 10 Hz, across both low and high stress states.

Cement stabilization and cement with SS-1 stabilization showed improved stiffness with regards to stabilizing GW and OGBC RAP specimens, over SS-1 emulsion stabilized specimens across mechanistic material properties. Vacuum saturation reduced the performance of the RAP materials. The effect of vacuum saturation differed depending on the type of RAP materials tested. Unstabilized GW RAP specimens failed in vacuum saturation. Two percent SS-1 emulsion stabilized GW RAP specimens failed in vacuum saturation prior to being tested at the high stress state. None of the OGBC RAP specimens failed during vacuum saturation testing; however, two percent SS-1 emulsion stabilized OGBC RAP VacSat specimens failed in the high stress state during the 0.5 Hz frequency sweep.

Overall, the OGBC RAP showed improved performance post moist cure and post vacuum saturation compared to the GW RAP. For example, the OGBC RAP specimens were generally stiffer than GW RAP specimens which are most likely due to the increased amount of fractured aggregate which improves aggregate particle interlock and its asphalt cement content.

RAP materials were used in City of Saskatoon test section rehabilitations as a base layer in the 2009 Green Streets Infrastructure Program.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

This research examined the use of RAP materials as an alternative material for COS road base courses. Although reclaimed asphalt pavement can have the greatest economic, environmental, and engineering impact in pavement recycling, the City of Saskatoon had yet to investigate the applications and performance of these RAP materials in road rehabilitation and construction. Determining technical feasibility of the City of Saskatoon's crushed RAP rubble materials is the first step towards demonstrating the economic, environmental, and social benefits of using RAP in an engineered road system.

6.1 Summary of Research Findings

The goal of this research project was to characterize crushed reclaimed asphalt pavement rubble materials as a structural base layer in City of Saskatoon pavement structures. With regards to the research objective, comparing the conventional and mechanistic behaviour of crushed RAP rubble materials across stabilization systems to conventional granular base material showed:

- During frequency sweep testing in the RaTT, the conventional granular base specimen failed at the high stress state. Climatic moisture conditioning was not carried out on the conventional granular base specimen.
- GW and OGBC RAP specimens had improved mechanistic material properties when compared to conventional granular base mechanistic material properties.
- Climatic moisture conditioning resulted in a reduction of mechanistic material properties for all unstabilized and cement and/or SS-1 emulsion stabilized RAP specimens. All unstabilized GW RAP specimens failed during vacuum saturation testing. The GW and OBGC RAP specimens stabilized with two percent SS-1 emulsion survived moisture conditioning, but failed during frequency sweep testing in the RaTT. All RAP specimens stabilized with cement and cement with SS-1 emulsion survived climatic moisture conditioning and frequency sweep testing.

- The dynamic modulus of the 2009 GW and OGBC RAP materials decreased with deviatoric stress (from low to high stress states) and decreased as frequency sweep decreased. Dynamic modulus of all RAP materials showed sensitivity to frequency. The OGBC RAP showed improved stiffness post moist cure and post vacuum saturation compared to the GW RAP; this is likely due to the increased amount of fractured aggregate and asphalt cement that improves aggregate particle interlock. Cement stabilization and cement with SS-1 stabilization improved the stiffness of GW and OGBC RAP specimens. Although vacuum saturation reduced the stiffness of the RAP specimens, the cement stabilized RAP specimens retained the highest stiffness.
- Poisson's ratio of the GW and OGBC RAP increased with deviatoric stress (from low to high stress states) and increased with each frequency level. Poisson's ratio of all RAP materials showed sensitivity to frequency. Poisson's ratio of GW and OGBC RAP specimens decreased with cement stabilization, and increased with SS-1 emulsion stabilization alone. Vacuum saturation further increased the Poisson's ratio of all stabilized specimens, including cement stabilized RAP specimens.
- The measured phase angle of the 2009 GW and OGBC RAP materials increased with deviatoric stress (from low to high stress states) and decreased with each frequency sweep. Phase angle results for the RAP materials were indicative of viscoelastic behaviour; a greater phase angle resulted due to a greater deviatoric stress state. Vacuum saturation increased the phase angle of the RAP specimens, as did stabilization with SS-1 emulsion.
- RaTT measured radial microstrain results of the 2009 GW and OGBC RAP materials showed that cement and cement with SS-1 emulsion stabilization improved the radial microstrain behavior of the RAP specimens. Radial microstrain increased with deviatoric stress (from low to high stress states) and decreased with each frequency sweep. The radial microstrain of all RAP materials showed sensitivity to frequency which was more pronounced at the high stress state, indicative of viscoelastic behaviour.
- The variability in material properties following vacuum saturation increased compared to the variability following moist cure. This trend was common across all

GW and OGBC RAP unstabilized and stabilized specimens but was particularly noticeable in the SS-1 emulsion stabilized specimens. This reflects the effect moisture has on the GW RAP material.

The City of Saskatoon demonstrated the technical feasibility of using RAP as a base layer in its Green Street Infrastructure Program test sections. The unit cost of crushed RAP material was less than the unit cost of virgin granular aggregate. With regards to the test section base layers constructed with RAP material base layers, the cost of RAP material was between 48 percent to 65 percent less than conventional virgin base material counterparts.

Additional observations resulting from this research project include:

- Impact crushing provided a higher fracture count for RAP materials, compared to conventional granular materials. This improved aggregate interlock during compaction. Also, by processing and crushing the RAP, a consistent gradation was generated; for example the GW RAP gradation met COS specifications for granular base materials.
- Both GW and OGBC RAP materials had residual asphalt contents which can be indicators of improved durability and increased moisture susceptibility of compacted specimens.
- The standard Proctor compaction method is not applicable for RAP materials due to the bound-nature of RAP aggregates, which are composed of asphalt and aggregate. RAP specimens expelled water during Proctor compaction and final compacted specimens were found to result in CBR values that do not accurately reflect field performance observations.
- Both GW and OGBC RAP materials (stabilized and unstabilized) could be tested in the RaTT. The vacuum saturation test provided an indication of climatic moisture durability of the RAP materials. Overall, the mechanistic-climatic laboratory program chosen for determining the performance of COS unstabilized and stabilized RAP materials worked well. This is likely due to the past knowledge of RaTT testing in Saskatchewan. However, the mechanistic-climatic characterization is limited because five (5) repeat samples were compacted and tested.

6.2 Conclusions

The hypothesis of this research was that City of Saskatoon processed and crushed RAP rubble materials can be used as a structural base layer in a recycled pavement structural system for Saskatoon's road rehabilitation systems. It was also hypothesized that recycled asphalt pavement road materials can provide economic benefits over conventional granular base materials.

The findings of this research indicate that RAP materials have improved mechanistic properties compared to conventional granular materials and are technical feasible to be used in Saskatoon's pavement base layers. This research also indicates that cement stabilization and cement with SS-1 stabilization (at a concentration of two percent cement or one percent cement with one percent SS-1) improved the moisture susceptibility of well graded (GW) and open graded base course (OGBC) RAP materials. These findings demonstrated that RAP materials stabilized with cement and/or SS-1 emulsion could be used as a base layer in a pavement structure.

Using RAP materials as a base layer costs less than conventional base materials; this demonstrates economic feasibility. The use of RAP materials in lieu of virgin aggregates reduces the pressure on the Saskatoon area's depleting aggregate sources and maximizes COS budget allocations.

6.3 Recommendations and Future Research

This research determined that it is feasible to use RAP materials as a base layer in City of Saskatoon rehabilitated road structures. Using RAP materials in road reconstruction is a sustainable and economically viable alternative to virgin aggregates. The mechanistic-climatic laboratory characterization performed in this research is limited because five (5) repeat samples were compacted and tested and a statistical analysis was not carried out.

Field measurements were limited because there was no construction sampling testing protocol employed and used in this research. This thesis focused on laboratory characterization and testing protocols for RAP materials. It is recommended that in the future, when a road is constructed with a RAP base layer, that an onsite sampling and laboratory testing program be conducted. With regards to test section layout, it is recommended that future test sections incorporating recycled materials be constructed with a control test section of conventional virgin materials to provide a comparison in the same field state conditions of both recycled aggregate and conventional aggregate pavement structures.

The following research studies are recommended as a continuation of this study, to examine long term effects of RAP material base layers:

- Monitor Green Street test section performance annually using non-destructive falling weight deflectometer testing and surface distress analysis.
- Document preservation and maintenance treatments.
- Conduct life-cycle costing (LCC) of all Green Street testing sections.
- Evaluate the effect of RAP removal and handling techniques. Evaluate the material properties and performance of the bitumen component of City of Saskatoon RAP material.
- Examine additional RaTT stress states for base layers, considering that the unstabilized conventional granular base failed in the high stress state.
- Conduct RaTT analysis at difference temperatures to examine the effect of temperature.
- Evaluate the performance and pavement response of each test section structure using a viscoelastic finite element model that incorporate mechanistic material properties and field state conditions.
- Assess the sustainability of the Green Street test sections and City of Saskatoon road construction and rehabilitation projects using a sustainability assessment program. It is recommended that Saskatchewan agencies either explore sustainability programs from other jurisdictions or develop a Saskatchewan-based sustainability program to assess the sustainability of road construction and rehabilitation operations.

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APPENDIX A. PRELIMINARY LABORATORY CHARACTERIZATION OF 2008 CRUSHED RAP RUBBLE MATERIALS

Table A.1 2009 GW RAP Dynamic Modulus across All Stress States

Base Material and Stabilization System	Dynamic Modulus (MPa) 10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	479	480	488	491
Unstabilized GW RAP	1111	1073	960	928
1.0% Cement GW RAP	1827	1772	1662	1664
2.0% Cement GW RAP	1782	1836	1714	1715
3.0% Cement GW RAP	1621	1606	1532	1516
1.0% SS-1 GW RAP	1658	1608	1405	1332
2.0% SS-1 GW RAP	2157	2091	1789	1667
3.0% SS-1 GW RAP	2055	1960	1704	1605
1.0% Cement, SS-1 GW RAP	1606	1601	1447	1420
2.0% Cement, SS-1 GW RAP	1914	1891	1709	1677
3.0% Cement, SS-1 GW RAP	2071	2009	1857	1790
Medium Stress State				
Conventional COS Granular Base	446	448	458	465
Unstabilized GW RAP	1138	1084	954	916
1.0% Cement GW RAP	2081	1961	1795	1760
2.0% Cement GW RAP	2011	1982	1863	1835
3.0% Cement GW RAP	1618	1605	1527	1521
1.0% SS-1 GW RAP	1717	1627	1395	1304
2.0% SS-1 GW RAP	2247	2090	1732	1618
3.0% SS-1 GW RAP	2201	2044	1691	1556
1.0% Cement, SS-1 GW RAP	1726	1633	1448	1378
2.0% Cement, SS-1 GW RAP	2069	1962	1735	1644
3.0% Cement, SS-1 GW RAP	2315	2167	1869	1781
High Stress State				
Conventional COS Granular Base	295	Failed	Failed	Failed
Unstabilized GW RAP	890	843	740	704
1.0% Cement GW RAP	1785	1620	1443	1388
2.0% Cement GW RAP	1772	1654	1487	1430
3.0% Cement GW RAP	1366	1276	1166	1146
1.0% SS-1 GW RAP	1381	1313	1096	1020
2.0% SS-1 GW RAP	1808	1691	1379	1255
3.0% SS-1 GW RAP	1860	1693	1355	1230
1.0% Cement, SS-1 GW RAP	1279	1258	1103	1033
2.0% Cement, SS-1 GW RAP	1703	1570	1345	1260
3.0% Cement, SS-1 GW RAP	1828	1708	1471	1383
Fully Reversed Stress State				
Conventional COS Granular Base	Failed	Failed	Failed	Failed
Unstabilized GW RAP	657	613	507	479
1.0% Cement GW RAP	1409	1200	1013	964
2.0% Cement GW RAP	1270	1216	1040	992
3.0% Cement GW RAP	923	876	747	720
1.0% SS-1 GW RAP	1113	1041	829	784
2.0% SS-1 GW RAP	1518	1384	1080	971
3.0% SS-1 GW RAP	1507	1372	1044	928
1.0% Cement, SS-1 GW RAP	969	912	764	710
2.0% Cement, SS-1 GW RAP	1300	1203	993	924
3.0% Cement, SS-1 GW RAP	1467	1379	1147	1072

Table A.2 2008 OGBC RAP Dynamic Modulus across All Stress States

Base Material and Stabilization System	Dynamic Modulus (MPa)			
	10 Hz	5 Hz	1 Hz	0.5 Hz
	Low Stress State			
Conventional COS Granular Base	479	480	488	491
Unstabilized OGBC RAP	1673	1581	1344	1269
1.0% Cement OGBC RAP	1727	1691	1449	1378
2.0% Cement OGBC RAP	2022	1879	1667	1597
3.0% Cement OGBC RAP	2198	2126	1951	1889
1.0% SS-1 OGBC RAP	1747	1593	1350	1258
2.0% SS-1 OGBC RAP	1738	1663	1398	1297
3.0% SS-1 OGBC RAP	2402	2331	1824	1668
1.0% Cement, SS-1 OGBC RAP	2086	2006	1814	1682
2.0% Cement, SS-1 OGBC RAP	1841	1800	1617	1555
3.0% Cement, SS-1 OGBC RAP	2076	2101	1838	1725
	Medium Stress State			
Conventional COS Granular Base	446	448	458	465
Unstabilized OGBC RAP	1650	1536	1298	1198
1.0% Cement OGBC RAP	1762	1679	1444	1358
2.0% Cement OGBC RAP	2006	1919	1656	1574
3.0% Cement OGBC RAP	2415	2329	2039	1947
1.0% SS-1 OGBC RAP	1745	1588	1319	1205
2.0% SS-1 OGBC RAP	1896	1728	1411	1288
3.0% SS-1 OGBC RAP	2477	2249	1785	1588
1.0% Cement, SS-1 OGBC RAP	2235	2079	1756	1623
2.0% Cement, SS-1 OGBC RAP	1982	1921	1660	1550
3.0% Cement, SS-1 OGBC RAP	2169	2180	1783	1660
	High Stress State			
Conventional COS Granular Base	295	Failed	Failed	Failed
Unstabilized OGBC RAP	1206	1150	972	901
1.0% Cement OGBC RAP	1301	1248	1073	1000
2.0% Cement OGBC RAP	1624	1515	1279	1178
3.0% Cement OGBC RAP	2050	1914	1616	1500
1.0% SS-1 OGBC RAP	1373	1255	1027	947
2.0% SS-1 OGBC RAP	1573	1417	1115	1008
3.0% SS-1 OGBC RAP	2084	1873	1424	1256
1.0% Cement, SS-1 OGBC RAP	1815	1639	1349	1232
2.0% Cement, SS-1 OGBC RAP	1460	1498	1264	1171
3.0% Cement, SS-1 OGBC RAP	1697	1735	1407	1285
	Fully Reversed Stress State			
Conventional COS Granular Base	Failed	Failed	Failed	Failed
Unstabilized OGBC RAP	882	825	665	604
1.0% Cement OGBC RAP	836	792	674	630
2.0% Cement OGBC RAP	1179	1085	875	807
3.0% Cement OGBC RAP	1456	1351	1120	1040
1.0% SS-1 OGBC RAP	1064	933	718	643
2.0% SS-1 OGBC RAP	1291	1155	850	747
3.0% SS-1 OGBC RAP	1781	1552	1133	980
1.0% Cement, SS-1 OGBC RAP	1336	1198	958	872
2.0% Cement, SS-1 OGBC RAP	1183	1149	939	858
3.0% Cement, SS-1 OGBC RAP	1354	1330	1038	935

Table A.3 2008 GW RAP Poisson's Ratio across All Stress States

Base Material and Stabilization System	Poisson's Ratio 10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	0.46	0.47	0.46	0.45
Unstabilized GW RAP	0.36	0.35	0.36	0.37
1.0% Cement GW RAP	0.19	0.22	0.26	0.23
2.0% Cement GW RAP	0.23	0.22	0.23	0.26
3.0% Cement GW RAP	0.19	0.19	0.21	0.21
1.0% SS-1 GW RAP	0.21	0.22	0.22	0.24
2.0% SS-1 GW RAP	0.19	0.23	0.23	0.22
3.0% SS-1 GW RAP	0.23	0.25	0.27	0.27
1.0% Cement, SS-1 GW RAP	0.24	0.24	0.23	0.26
2.0% Cement, SS-1 GW RAP	0.20	0.21	0.23	0.23
3.0% Cement, SS-1 GW RAP	0.22	0.17	0.21	0.19
Medium Stress State				
Conventional COS Granular Base	0.62	0.63	0.62	0.61
Unstabilized GW RAP	0.41	0.43	0.44	0.44
1.0% Cement GW RAP	0.25	0.25	0.28	0.29
2.0% Cement GW RAP	0.25	0.26	0.29	0.29
3.0% Cement GW RAP	0.22	0.23	0.25	0.27
1.0% SS-1 GW RAP	0.27	0.27	0.29	0.29
2.0% SS-1 GW RAP	0.25	0.25	0.26	0.28
3.0% SS-1 GW RAP	0.29	0.29	0.32	0.33
1.0% Cement, SS-1 GW RAP	0.29	0.29	0.31	0.31
2.0% Cement, SS-1 GW RAP	0.25	0.25	0.28	0.28
3.0% Cement, SS-1 GW RAP	0.22	0.24	0.24	0.24
High Stress State				
Conventional COS Granular Base	1.00	Failed	Failed	Failed
Unstabilized GW RAP	0.52	0.54	0.58	0.59
1.0% Cement GW RAP	0.33	0.34	0.37	0.38
2.0% Cement GW RAP	0.28	0.29	0.32	0.34
3.0% Cement GW RAP	0.27	0.28	0.31	0.34
1.0% SS-1 GW RAP	0.30	0.33	0.38	0.40
2.0% SS-1 GW RAP	0.28	0.29	0.34	0.36
3.0% SS-1 GW RAP	0.32	0.34	0.37	0.40
1.0% Cement, SS-1 GW RAP	0.36	0.38	0.42	0.44
2.0% Cement, SS-1 GW RAP	0.31	0.32	0.35	0.37
3.0% Cement, SS-1 GW RAP	0.25	0.27	0.30	0.33
Fully Reversed Stress State				
Conventional COS Granular Base	Failed	Failed	Failed	Failed
Unstabilized GW RAP	0.39	0.41	0.41	0.41
1.0% Cement GW RAP	0.28	0.27	0.28	0.29
2.0% Cement GW RAP	0.25	0.25	0.27	0.28
3.0% Cement GW RAP	0.29	0.29	0.29	0.31
1.0% SS-1 GW RAP	0.26	0.27	0.29	0.29
2.0% SS-1 GW RAP	0.25	0.27	0.28	0.28
3.0% SS-1 GW RAP	0.30	0.30	0.33	0.32
1.0% Cement, SS-1 GW RAP	0.31	0.31	0.33	0.34
2.0% Cement, SS-1 GW RAP	0.25	0.26	0.27	0.28
3.0% Cement, SS-1 GW RAP	0.22	0.24	0.25	0.24

Table A.4 2008 OGBC RAP Poisson's Ratio across All Stress States

Base Material and Stabilization System	Poisson's Ratio			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	0.46	0.47	0.46	0.45
Unstabilized OGBC RAP	0.22	0.23	0.24	0.25
1.0% Cement OGBC RAP	0.24	0.30	0.29	0.31
2.0% Cement OGBC RAP	0.26	0.22	0.26	0.28
3.0% Cement OGBC RAP	0.22	0.17	0.18	0.20
1.0% SS-1 OGBC RAP	0.28	0.26	0.31	0.30
2.0% SS-1 OGBC RAP	0.26	0.27	0.28	0.28
3.0% SS-1 OGBC RAP	0.18	0.20	0.21	0.22
1.0% Cement, SS-1 OGBC RAP	0.24	0.24	0.25	0.28
2.0% Cement, SS-1 OGBC RAP	0.19	0.18	0.20	0.21
3.0% Cement, SS-1 OGBC RAP	0.23	0.21	0.20	0.21
Medium Stress State				
Conventional COS Granular Base	0.62	0.63	0.62	0.61
Unstabilized OGBC RAP	0.28	0.29	0.31	0.33
1.0% Cement OGBC RAP	0.29	0.28	0.31	0.33
2.0% Cement OGBC RAP	0.29	0.31	0.32	0.32
3.0% Cement OGBC RAP	0.22	0.24	0.27	0.29
1.0% SS-1 OGBC RAP	0.31	0.31	0.35	0.35
2.0% SS-1 OGBC RAP	0.28	0.31	0.32	0.34
3.0% SS-1 OGBC RAP	0.25	0.27	0.28	0.28
1.0% Cement, SS-1 OGBC RAP	0.32	0.32	0.32	0.33
2.0% Cement, SS-1 OGBC RAP	0.24	0.25	0.29	0.29
3.0% Cement, SS-1 OGBC RAP	0.26	0.25	0.27	0.30
High Stress State				
Conventional COS Granular Base	1.00	Failed	Failed	Failed
Unstabilized OGBC RAP	0.32	0.35	0.40	0.43
1.0% Cement OGBC RAP	0.30	0.33	0.37	0.40
2.0% Cement OGBC RAP	0.32	0.34	0.38	0.40
3.0% Cement OGBC RAP	0.25	0.25	0.28	0.32
1.0% SS-1 OGBC RAP	0.33	0.36	0.41	0.45
2.0% SS-1 OGBC RAP	0.31	0.34	0.38	0.41
3.0% SS-1 OGBC RAP	0.27	0.29	0.32	0.35
1.0% Cement, SS-1 OGBC RAP	0.39	0.39	0.43	0.45
2.0% Cement, SS-1 OGBC RAP	0.26	0.29	0.34	0.37
3.0% Cement, SS-1 OGBC RAP	0.26	0.29	0.34	0.36
Fully Reversed Stress State				
Conventional COS Granular Base	Failed	Failed	Failed	Failed
Unstabilized OGBC RAP	0.28	0.29	0.31	0.33
1.0% Cement OGBC RAP	0.23	0.24	0.27	0.28
2.0% Cement OGBC RAP	0.28	0.29	0.31	0.31
3.0% Cement OGBC RAP	0.20	0.19	0.23	0.24
1.0% SS-1 OGBC RAP	0.30	0.31	0.34	0.35
2.0% SS-1 OGBC RAP	0.29	0.31	0.34	0.34
3.0% SS-1 OGBC RAP	0.26	0.26	0.29	0.29
1.0% Cement, SS-1 OGBC RAP	0.31	0.30	0.33	0.34
2.0% Cement, SS-1 OGBC RAP	0.22	0.25	0.27	0.30
3.0% Cement, SS-1 OGBC RAP	0.22	0.25	0.28	0.28

Table A.5 2008 GW RAP Phase Angle across All Stress States

Base Material and Stabilization System	Phase Angle (degrees)			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	8.6	6.9	5.3	5.1
Unstabilized GW RAP	16.1	14.3	13.3	12.3
1.0% Cement GW RAP	12.2	11.8	11.9	11.8
2.0% Cement GW RAP	13.2	11.1	10.9	10.6
3.0% Cement GW RAP	11.7	10.4	10.3	10.0
1.0% SS-1 GW RAP	15.3	14.6	12.9	13.6
2.0% SS-1 GW RAP	15.4	14.3	14.1	13.9
3.0% SS-1 GW RAP	15.5	15.7	15.0	14.9
1.0% Cement, SS-1 GW RAP	13.4	12.1	11.4	11.0
2.0% Cement, SS-1 GW RAP	12.9	12.0	11.9	11.9
3.0% Cement, SS-1 GW RAP	12.8	10.5	10.2	10.8
Medium Stress State				
Conventional COS Granular Base	10.9	9.1	7.2	6.8
Unstabilized GW RAP	17.1	15.4	14.0	13.5
1.0% Cement GW RAP	14.4	13.6	13.3	12.6
2.0% Cement GW RAP	14.4	13.0	13.0	12.6
3.0% Cement GW RAP	13.9	12.8	12.4	12.4
1.0% SS-1 GW RAP	16.4	15.1	14.2	14.1
2.0% SS-1 GW RAP	16.3	15.5	15.0	15.0
3.0% SS-1 GW RAP	17.2	15.7	15.7	15.6
1.0% Cement, SS-1 GW RAP	14.7	13.7	12.7	12.8
2.0% Cement, SS-1 GW RAP	13.8	12.9	12.5	12.8
3.0% Cement, SS-1 GW RAP	16.0	14.7	13.0	12.1
High Stress State				
Conventional COS Granular Base	15.2	Failed	Failed	Failed
Unstabilized GW RAP	18.9	17.2	16.0	15.3
1.0% Cement GW RAP	15.4	15.7	14.4	14.3
2.0% Cement GW RAP	17.2	14.3	14.0	14.1
3.0% Cement GW RAP	16.0	14.5	14.3	14.1
1.0% SS-1 GW RAP	18.1	16.6	16.0	15.9
2.0% SS-1 GW RAP	18.5	16.6	16.3	16.6
3.0% SS-1 GW RAP	18.9	17.4	17.2	17.3
1.0% Cement, SS-1 GW RAP	17.6	15.1	14.6	14.7
2.0% Cement, SS-1 GW RAP	16.0	15.3	14.6	14.4
3.0% Cement, SS-1 GW RAP	14.8	14.3	14.0	14.1
Fully Reversed Stress State				
Conventional COS Granular Base	Failed	Failed	Failed	Failed
Unstabilized GW RAP	19.8	18.6	17.8	17.5
1.0% Cement GW RAP	14.7	15.8	15.4	15.0
2.0% Cement GW RAP	15.2	14.1	14.3	14.1
3.0% Cement GW RAP	16.3	15.3	14.8	14.9
1.0% SS-1 GW RAP	19.0	18.1	17.7	17.5
2.0% SS-1 GW RAP	18.1	17.3	17.8	18.2
3.0% SS-1 GW RAP	20.4	18.8	19.0	19.1
1.0% Cement, SS-1 GW RAP	18.1	17.0	16.3	16.3
2.0% Cement, SS-1 GW RAP	16.8	15.9	15.4	15.3
3.0% Cement, SS-1 GW RAP	14.8	14.3	14.8	14.7

Table A.6 2008 OGBC RAP Phase Angle across All Stress States

Base Material and Stabilization System	Phase Angle (degrees)			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	8.6	6.9	5.3	5.1
Unstabilized OGBC RAP	15.8	13.5	13.0	13.0
1.0% Cement OGBC RAP	14.0	11.2	11.8	10.8
2.0% Cement OGBC RAP	14.1	13.3	11.8	11.5
3.0% Cement OGBC RAP	14.0	11.5	11.6	11.0
1.0% SS-1 OGBC RAP	16.6	14.8	14.2	13.8
2.0% SS-1 OGBC RAP	16.7	16.0	15.1	15.7
3.0% SS-1 OGBC RAP	18.1	16.5	16.3	16.3
1.0% Cement, SS-1 OGBC RAP	14.8	12.5	12.5	12.6
2.0% Cement, SS-1 OGBC RAP	14.8	13.1	11.7	13.2
3.0% Cement, SS-1 OGBC RAP	15.1	13.8	13.5	13.2
Medium Stress State				
Conventional COS Granular Base	10.9	9.1	7.2	6.8
Unstabilized OGBC RAP	15.9	14.7	14.0	13.6
1.0% Cement OGBC RAP	15.7	13.4	12.9	12.5
2.0% Cement OGBC RAP	14.9	13.2	12.7	12.9
3.0% Cement OGBC RAP	14.1	12.4	12.7	12.4
1.0% SS-1 OGBC RAP	17.6	15.7	15.0	14.9
2.0% SS-1 OGBC RAP	17.9	16.8	16.3	16.2
3.0% SS-1 OGBC RAP	18.6	17.0	16.8	17.0
1.0% Cement, SS-1 OGBC RAP	14.9	14.1	13.6	13.9
2.0% Cement, SS-1 OGBC RAP	16.2	13.9	13.2	13.2
3.0% Cement, SS-1 OGBC RAP	19.3	16.5	15.1	14.6
High Stress State				
Conventional COS Granular Base	15.2	Failed	Failed	Failed
Unstabilized OGBC RAP	16.8	15.1	14.4	14.3
1.0% Cement OGBC RAP	15.4	14.2	13.5	13.1
2.0% Cement OGBC RAP	15.8	14.7	14.4	14.1
3.0% Cement OGBC RAP	15.4	14.2	13.9	14.2
1.0% SS-1 OGBC RAP	17.2	16.7	15.9	15.9
2.0% SS-1 OGBC RAP	19.7	18.5	18.1	17.8
3.0% SS-1 OGBC RAP	20.0	19.2	18.9	18.7
1.0% Cement, SS-1 OGBC RAP	16.9	16.1	15.4	15.5
2.0% Cement, SS-1 OGBC RAP	18.4	14.8	14.3	14.4
3.0% Cement, SS-1 OGBC RAP	20.1	16.5	16.2	15.8
Fully Reversed Stress State				
Conventional COS Granular Base	Failed	Failed	Failed	Failed
Unstabilized OGBC RAP	18.0	17.1	17.1	17.3
1.0% Cement OGBC RAP	15.6	14.4	14.0	13.9
2.0% Cement OGBC RAP	16.9	16.1	16.1	16.1
3.0% Cement OGBC RAP	15.7	14.9	14.7	14.8
1.0% SS-1 OGBC RAP	20.2	19.2	18.9	18.8
2.0% SS-1 OGBC RAP	22.4	21.1	21.0	20.8
3.0% SS-1 OGBC RAP	20.4	19.9	20.6	20.9
1.0% Cement, SS-1 OGBC RAP	17.4	16.8	17.0	17.3
2.0% Cement, SS-1 OGBC RAP	17.8	16.0	16.2	16.7
3.0% Cement, SS-1 OGBC RAP	21.0	18.3	18.0	17.9

Table A.7 2008 GW RAP Radial Microstrain across All Stress States

Base Material and Stabilization System	Radial Microstrain 10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	185	190	186	181
Unstabilized GW RAP	64	63	75	79
1.0% Cement GW RAP	21	25	31	27
2.0% Cement GW RAP	25	24	26	30
3.0% Cement GW RAP	22	24	27	27
1.0% SS-1 GW RAP	25	27	31	36
2.0% SS-1 GW RAP	17	22	25	26
3.0% SS-1 GW RAP	22	25	32	34
1.0% Cement, SS-1 GW RAP	30	30	32	36
2.0% Cement, SS-1 GW RAP	20	22	27	27
3.0% Cement, SS-1 GW RAP	14	16	22	21
Medium Stress State				
Conventional COS Granular Base	542	551	533	516
Unstabilized GW RAP	139	156	183	190
1.0% Cement GW RAP	47	50	62	64
2.0% Cement GW RAP	49	52	62	63
3.0% Cement GW RAP	52	57	65	70
1.0% SS-1 GW RAP	62	65	84	90
2.0% SS-1 GW RAP	44	47	60	69
3.0% SS-1 GW RAP	51	56	76	84
1.0% Cement, SS-1 GW RAP	65	70	85	89
2.0% Cement, SS-1 GW RAP	48	51	64	67
3.0% Cement, SS-1 GW RAP	36	44	51	54
High Stress State				
Conventional COS Granular Base	1815	Failed	Failed	Failed
Unstabilized GW RAP	309	348	429	459
1.0% Cement GW RAP	99	115	141	151
2.0% Cement GW RAP	84	95	118	130
3.0% Cement GW RAP	106	120	148	164
1.0% SS-1 GW RAP	116	138	188	212
2.0% SS-1 GW RAP	81	94	134	159
3.0% SS-1 GW RAP	93	108	150	178
1.0% Cement, SS-1 GW RAP	149	166	211	231
2.0% Cement, SS-1 GW RAP	96	110	142	161
3.0% Cement, SS-1 GW RAP	74	84	112	130
Fully Reversed Stress State				
Conventional COS Granular Base	Failed	Failed	Failed	Failed
Unstabilized GW RAP	239	263	318	341
1.0% Cement GW RAP	79	88	111	118
2.0% Cement GW RAP	78	83	104	112
3.0% Cement GW RAP	124	131	156	169
1.0% SS-1 GW RAP	93	101	138	151
2.0% SS-1 GW RAP	65	77	103	115
3.0% SS-1 GW RAP	81	88	126	139
1.0% Cement, SS-1 GW RAP	126	137	174	191
2.0% Cement, SS-1 GW RAP	77	86	108	120
3.0% Cement, SS-1 GW RAP	59	70	87	96

Table A.8 2008 OGBC RAP Radial Microstrain across All Stress States

Base Material and Stabilization System	Radial Microstrain			
	10 Hz	5 Hz	1 Hz	0.5 Hz
Low Stress State				
Conventional COS Granular Base	185	190	186	181
Unstabilized OGBC RAP	26	28	35	39
1.0% Cement OGBC RAP	27	35	39	43
2.0% Cement OGBC RAP	25	23	30	35
3.0% Cement OGBC RAP	19	16	19	21
1.0% SS-1 OGBC RAP	31	33	45	47
2.0% SS-1 OGBC RAP	29	32	40	42
3.0% SS-1 OGBC RAP	15	18	23	26
1.0% Cement, SS-1 OGBC RAP	23	23	27	33
2.0% Cement, SS-1 OGBC RAP	20	20	25	27
3.0% Cement, SS-1 OGBC RAP	22	20	22	24
Medium Stress State				
Conventional COS Granular Base	542	551	533	516
Unstabilized OGBC RAP	66	75	97	110
1.0% Cement OGBC RAP	63	66	85	92
2.0% Cement OGBC RAP	57	64	77	82
3.0% Cement OGBC RAP	36	40	53	59
1.0% SS-1 OGBC RAP	70	76	105	116
2.0% SS-1 OGBC RAP	58	71	91	104
3.0% SS-1 OGBC RAP	39	47	62	71
1.0% Cement, SS-1 OGBC RAP	55	61	74	80
2.0% Cement, SS-1 OGBC RAP	46	51	69	74
3.0% Cement, SS-1 OGBC RAP	46	46	61	72
High Stress State				
Conventional COS Granular Base	1815	Failed	Failed	Failed
Unstabilized OGBC RAP	143	167	228	265
1.0% Cement OGBC RAP	124	145	190	218
2.0% Cement OGBC RAP	105	121	164	184
3.0% Cement OGBC RAP	65	69	96	115
1.0% SS-1 OGBC RAP	129	155	218	258
2.0% SS-1 OGBC RAP	107	129	189	226
3.0% SS-1 OGBC RAP	68	84	122	151
1.0% Cement, SS-1 OGBC RAP	114	128	175	200
2.0% Cement, SS-1 OGBC RAP	97	106	148	174
3.0% Cement, SS-1 OGBC RAP	81	91	133	155
Fully Reversed Stress State				
Conventional COS Granular Base	Failed	Failed	Failed	Failed
Unstabilized OGBC RAP	125	138	187	214
1.0% Cement OGBC RAP	110	119	158	176
2.0% Cement OGBC RAP	95	106	139	152
3.0% Cement OGBC RAP	55	57	81	91
1.0% SS-1 OGBC RAP	111	130	188	214
2.0% SS-1 OGBC RAP	89	107	158	183
3.0% SS-1 OGBC RAP	59	66	101	118
1.0% Cement, SS-1 OGBC RAP	93	99	136	155
2.0% Cement, SS-1 OGBC RAP	74	85	114	140
3.0% Cement, SS-1 OGBC RAP	64	76	108	118

APPENDIX B. REPEAT SAMPLE TESTING – MECHANISTIC STRENGTHENING ANALYSIS (2009 GW AND OGBC RAP MATERIALS)

Table B.1 2009 GW RAP Dynamic Modulus across All Stress States

GW RAP with Stabilizer	Sample	Dynamic Modulus (MPa)															
		Low Stress State				Medium Stress State				High Stress State				Fully Reversed Stress State			
		10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz
0% (MC)	1	1653	1569	1375	1314	1631	1553	1367	1291	1271	1204	1048	987	979	915	764	712
	2	1548	1525	1352	1312	1607	1521	1348	1277	1229	1166	1023	959	904	848	718	669
	3	1542	1513	1379	1334	1582	1519	1370	1301	1245	1190	1048	990	933	886	753	704
	4	1433	1392	1274	1234	1510	1438	1289	1226	1169	1111	982	928	848	803	682	639
	5	1456	1425	1300	1251	1523	1439	1296	1240	1153	1101	978	932	823	781	667	628
0% (VacSat)	1	422	404	362	359	461	763	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2% Cem (MC)	1	2390	2340	2217	2131	2510	2418	2190	2085	2037	1963	1716	1631	1598	1531	1318	1246
	2	2565	2503	2276	2245	2690	2551	2320	2236	2185	2074	1831	1746	1695	1600	1371	1301
	3	2749	2837	2590	2555	2820	2738	2485	2419	2377	2241	2002	1901	1875	1800	1569	1492
	4	2538	2436	2217	2210	2541	2395	2186	2111	2113	1992	1739	1647	1623	1526	1307	1223
	5	2432	2375	2191	2094	2461	2371	2122	2071	2003	1899	1665	1589	1544	1463	1276	1206
2% Cem (VacSat)	1	1554	1556	1413	1347	1734	1653	1448	1362	1363	1290	1122	1065	845	763	592	449
	2	1751	1714	1584	1569	1922	1844	1640	1606	1509	1416	1232	1162	1079	1011	843	786
	3	1894	1836	1717	1722	2095	1966	1745	1688	1681	1573	1368	1294	1192	1121	946	891
	4	1735	1696	1551	1537	1896	1804	1606	1553	1492	1390	1208	1136	958	887	717	662
	5	1911	1874	1678	1653	2080	1938	1736	1648	1594	1482	1282	1203	1108	1036	855	792
2% SS-1 (MC)	1	1621	1495	1233	1147	1620	1468	1197	1107	1313	1180	948	866	1054	921	682	608
	2	1646	1529	1260	1172	1688	1520	1236	1137	1369	1225	968	880	1085	946	697	617
	3	1635	1500	1253	1160	1643	1494	1221	1134	1336	1214	964	882	1070	945	704	626
	4	1461	1345	1122	1056	1505	1357	1115	1036	1229	1095	891	822	971	847	631	564
	5	1642	1526	1261	1164	1653	1498	1219	1123	1325	1202	964	884	1051	932	686	609
2% SS-1 (VacSat)	1	484	493	946	990	606	561	490	488	533	494	481	-	-	-	-	-
	2	699	661	592	588	793	739	636	610	-	-	-	-	-	-	-	-
	3	725	687	574	535	705	640	526	485	-	-	-	-	-	-	-	-
	4	831	800	685	659	890	817	683	649	642	593	467	-	-	-	-	-
	5	590	537	442	414	648	598	494	455	-	-	-	-	-	-	-	-
2% Cem/SS-1 (MC)	1	1873	1783	1589	1543	1897	1818	1581	1503	1501	1425	1206	1124	1155	1084	898	835
	2	1678	1631	1457	1409	1849	1716	1505	1434	1472	1352	1152	1071	1102	1020	842	784
	3	1843	1754	1571	1517	1941	1774	1576	1500	1537	1411	1201	1121	1168	1066	891	832
	4	1730	1659	1496	1447	1784	1677	1471	1406	1410	1309	1133	1069	1032	957	787	734
	5	1769	1738	1551	1478	1804	1720	1502	1402	1327	1249	1065	996	991	927	770	717
2% Cem/SS-1 (VacSat)	1	1477	1329	1136	1056	1386	1221	1001	886	993	893	742	695	727	629	459	374
	2	1171	1116	971	923	1259	1158	982	915	893	820	684	635	560	506	384	333
	3	1244	1179	1034	973	1302	1173	989	899	900	834	681	628	514	462	353	328
	4	1071	993	844	774	1173	1073	909	836	930	851	707	651	444	373	174	111
	5	1203	1087	931	835	1221	1065	853	809	905	829	687	638	457	344	106	98

Table B.2 2009 OGBC RAP Dynamic Modulus across All Stress States

OGBC RAP with Stabilizer	Sample	Dynamic Modulus (MPa)															
		Low Stress State				Medium Stress State				High Stress State				Fully Reversed Stress State			
		10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz
0% (MC)	1	2140	2009	1659	1518	2379	2171	1698	1526	1993	1809	1386	1232	1647	1496	1103	972
	2	2174	2055	1723	1548	2365	2133	1712	1533	1993	1803	1394	1242	1664	1506	1124	991
	3	1973	1868	1518	1401	2190	1975	1573	1435	1910	1715	1332	1195	1604	1432	1061	930
	4	1933	1805	1505	1388	2137	1951	1545	1411	1834	1652	1277	1141	1483	1336	981	864
	5	2144	1978	1623	1504	2426	2120	1669	1518	2051	1799	1374	1236	1730	1514	1110	970
0% (VacSat)	1	1637	1524	1192	1082	1746	1561	1199	1065	1386	1223	937	842	888	757	465	340
	2	1552	1404	1089	994	1603	1421	1101	981	1230	1109	859	770	695	580	312	219
	3	1404	1277	1011	918	1456	1292	1002	905	1188	1060	819	741	272	226	139	106
	4	1517	1387	1113	1024	1536	1385	1087	983	1221	1084	847	763	812	701	475	385
	5	1596	1453	1127	1026	1680	1478	1143	1019	1249	1091	870	806	746	617	343	204
2% Cem (MC)	1	2021	1979	1727	1666	2419	2229	1867	1733	2059	1881	1532	1399	1668	1505	1165	1040
	2	2150	2053	1818	1733	2423	2203	1870	1756	2161	1996	1606	1472	1777	1620	1236	1114
	3	2283	2208	1903	1713	2599	2406	1956	1808	2072	1910	1529	1389	1695	1553	1197	1073
	4	2407	2205	1931	1830	2605	2376	1999	1869	2246	2007	1619	1490	1768	1579	1234	1121
	5	2106	2007	1742	1627	2345	2167	1812	1679	2053	1843	1480	1356	1638	1476	1126	1007
2% Cem (VacSat)	1	2274	2109	1734	1637	2517	2277	1820	1658	1964	1792	1393	1260	1558	1372	994	870
	2	2033	1916	1613	1505	2207	2049	1641	1500	1836	1675	1309	1186	1361	1213	885	767
	3	2181	2047	1736	1626	2396	2195	1773	1615	1907	1720	1352	1217	1477	1328	993	880
	4	2229	2083	1825	1723	2528	2307	1885	1738	2033	1862	1471	1335	1572	1417	1064	951
	5	2141	1966	1662	1574	2421	2188	1723	1595	1908	1710	1333	1203	1462	1298	960	840
2% SS-1 (MC)	1	1820	1644	1268	1176	1994	1728	1294	1157	1723	1497	1083	956	1512	1271	835	701
	2	1897	1717	1301	1176	1982	1746	1304	1160	1689	1467	1067	944	1470	1239	804	684
	3	2025	1796	1385	1238	2094	1828	1353	1186	1775	1528	1097	954	1542	1266	820	685
	4	1692	1496	1161	1064	1789	1568	1182	1063	1553	1338	976	864	1335	1114	729	625
	5	1761	1582	1251	1137	1918	1710	1273	1129	1679	1472	1054	921	1469	1247	804	672
2% SS-1 (VacSat)	1	1114	984	709	630	1288	1107	802	701	1088	935	682	-	-	-	-	-
	2	1187	1038	765	679	1332	1148	846	752	1071	922	657	-	-	-	-	-
	3	1230	1072	790	699	1341	1152	835	738	1131	977	717	632	730	605	386	340
	4	851	755	565	510	986	860	652	592	842	741	540	-	-	-	-	-
	5	1142	1031	765	699	1340	1160	860	761	1110	957	704	610	-	-	-	-
2% Cem/SS-1 (MC)	1	2200	1985	1681	1566	2506	2189	1751	1589	2215	1936	1464	1304	1986	1716	1229	1077
	2	2094	1985	1641	1528	2420	2220	1751	1581	2114	1896	1442	1291	1863	1655	1201	1047
	3	2237	2048	1710	1619	2582	2317	1805	1649	2315	2015	1515	1342	2062	1760	1234	1076
	4	2343	2057	1643	1514	2524	2191	1687	1545	2222	1933	1442	1283	1873	1626	1127	975
	5	2255	2107	1709	1591	2520	2260	1772	1607	2242	1958	1465	1297	1948	1690	1189	1033
2% Cem/SS-1 (VacSat)	1	1857	1639	1262	1142	2123	1824	1348	1192	1789	1520	1093	953	1065	777	452	318
	2	2206	1964	1512	1358	2238	1989	1497	1333	1827	1597	1171	1032	1411	1219	817	692
	3	2039	1874	1423	1290	2226	1956	1442	1271	1900	1643	1170	1028	1427	1189	740	529
	4	2193	2011	1563	1389	2396	2121	1584	1424	1990	1752	1282	1132	1580	1361	925	786
	5	2203	2012	1576	1416	2375	2061	1573	1385	1961	1691	1236	1085	1480	1255	841	696

Table B.3 2009 GW RAP Poisson's Ratio across All Stress States

GW RAP with Stabilizer	Sample	Poisson's Ratio															
		Low Stress State				Medium Stress State				High Stress State				Fully Reversed Stress State			
		10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz
0% (MC)	1	0.22	0.22	0.23	0.26	0.26	0.26	0.28	0.29	0.30	0.31	0.35	0.37	0.25	0.26	0.27	0.28
	2	0.16	0.18	0.19	0.22	0.23	0.22	0.25	0.25	0.29	0.30	0.35	0.37	0.24	0.24	0.26	0.27
	3	0.17	0.17	0.20	0.17	0.22	0.22	0.24	0.25	0.28	0.29	0.33	0.35	0.22	0.22	0.25	0.27
	4	0.20	0.21	0.22	0.23	0.27	0.26	0.28	0.29	0.35	0.36	0.40	0.42	0.26	0.28	0.30	0.30
	5	0.23	0.22	0.23	0.25	0.28	0.28	0.30	0.31	0.35	0.37	0.41	0.43	0.28	0.29	0.30	0.32
0% (VacSat)	1	0.44	0.45	0.50	0.50	0.52	0.97	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2% Cem (MC)	1	0.13	0.14	0.15	0.14	0.17	0.17	0.20	0.20	0.21	0.21	0.22	0.23	0.16	0.16	0.15	0.16
	2	0.16	0.13	0.14	0.18	0.22	0.22	0.21	0.23	0.23	0.23	0.25	0.26	0.18	0.20	0.20	0.22
	3	0.12	0.14	0.16	0.14	0.17	0.19	0.18	0.19	0.20	0.19	0.21	0.23	0.14	0.14	0.16	0.17
	4	0.12	0.15	0.14	0.14	0.16	0.15	0.16	0.18	0.19	0.19	0.20	0.23	0.15	0.14	0.16	0.16
	5	0.15	0.12	0.13	0.16	0.14	0.15	0.17	0.16	0.18	0.19	0.21	0.21	0.14	0.14	0.16	0.16
2% Cem (VacSat)	1	0.15	0.14	0.15	0.15	0.21	0.21	0.22	0.24	0.26	0.26	0.30	0.33	0.18	0.19	0.19	0.17
	2	0.13	0.15	0.15	0.17	0.20	0.20	0.22	0.23	0.26	0.26	0.30	0.32	0.19	0.19	0.21	0.22
	3	0.09	0.09	0.09	0.11	0.16	0.14	0.18	0.16	0.22	0.22	0.24	0.27	0.15	0.15	0.17	0.18
	4	0.12	0.12	0.16	0.16	0.17	0.16	0.17	0.19	0.20	0.22	0.26	0.29	0.18	0.18	0.19	0.20
	5	0.14	0.14	0.17	0.15	0.18	0.19	0.21	0.21	0.22	0.21	0.25	0.27	0.16	0.18	0.19	0.19
2% SS-1 (MC)	1	0.27	0.26	0.29	0.29	0.29	0.31	0.33	0.34	0.33	0.34	0.41	0.43	0.30	0.32	0.35	0.35
	2	0.28	0.26	0.28	0.29	0.29	0.33	0.34	0.36	0.35	0.37	0.42	0.44	0.31	0.32	0.34	0.36
	3	0.22	0.24	0.26	0.26	0.27	0.28	0.31	0.33	0.32	0.34	0.40	0.42	0.27	0.29	0.32	0.32
	4	0.21	0.22	0.24	0.23	0.27	0.27	0.31	0.31	0.31	0.32	0.38	0.40	0.27	0.30	0.34	0.35
	5	0.24	0.23	0.24	0.26	0.26	0.27	0.30	0.32	0.32	0.33	0.40	0.42	0.25	0.29	0.31	0.32
2% SS-1 (VacSat)	1	0.45	0.44	0.84	0.79	0.49	0.52	0.53	0.51	0.60	0.64	0.81	-	-	-	-	-
	2	0.39	0.39	0.39	0.37	0.43	0.44	0.45	0.45	-	-	-	-	-	-	-	-
	3	0.31	0.31	0.33	0.34	0.43	0.44	0.50	0.52	-	-	-	-	-	-	-	-
	4	0.33	0.33	0.32	0.33	0.38	0.39	0.40	0.41	0.56	0.58	0.66	-	-	-	-	-
	5	0.47	0.50	0.54	0.58	0.55	0.57	0.64	0.67	-	-	-	-	-	-	-	-
2% Cem/SS-1 (MC)	1	0.20	0.19	0.21	0.21	0.23	0.25	0.27	0.27	0.30	0.32	0.35	0.36	0.23	0.23	0.26	0.26
	2	0.10	0.10	0.14	0.12	0.17	0.17	0.18	0.20	0.23	0.24	0.29	0.31	0.17	0.17	0.19	0.19
	3	0.14	0.15	0.13	0.15	0.20	0.18	0.20	0.20	0.28	0.28	0.30	0.32	0.20	0.20	0.22	0.22
	4	0.20	0.20	0.24	0.22	0.27	0.27	0.29	0.31	0.34	0.35	0.39	0.43	0.28	0.29	0.31	0.32
	5	0.13	0.12	0.16	0.17	0.22	0.21	0.23	0.24	0.26	0.28	0.33	0.35	0.19	0.21	0.24	0.26
2% Cem/SS-1 (VacSat)	1	0.37	0.38	0.37	0.37	0.42	0.41	0.44	0.47	0.60	0.59	0.62	0.63	0.29	0.28	0.29	0.29
	2	0.22	0.23	0.24	0.23	0.27	0.27	0.29	0.30	0.41	0.44	0.50	0.52	0.24	0.24	0.25	0.25
	3	0.16	0.16	0.17	0.18	0.22	0.21	0.24	0.26	0.35	0.38	0.44	0.47	0.25	0.26	0.27	0.28
	4	0.25	0.25	0.28	0.29	0.32	0.33	0.35	0.39	0.44	0.47	0.51	0.55	0.31	0.31	0.27	0.25
	5	0.20	0.23	0.21	0.22	0.27	0.31	0.35	0.37	0.44	0.47	0.52	0.56	0.32	0.30	0.17	0.19

Table B.4 2009 OGBC RAP Poisson's Ratio across All Stress States

OGBC RAP with Stabilizer	Sample	Poisson's Ratio															
		Low Stress State				Medium Stress State				High Stress State				Fully Reversed Stress State			
		10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz
0% (MC)	1	0.22	0.22	0.23	0.26	0.24	0.24	0.28	0.29	0.25	0.26	0.31	0.34	0.22	0.24	0.27	0.29
	2	0.16	0.22	0.24	0.21	0.23	0.23	0.24	0.26	0.26	0.25	0.29	0.31	0.20	0.23	0.26	0.26
	3	0.18	0.20	0.21	0.23	0.24	0.25	0.26	0.27	0.24	0.27	0.31	0.32	0.24	0.23	0.28	0.30
	4	0.17	0.18	0.20	0.21	0.21	0.21	0.25	0.27	0.23	0.24	0.29	0.32	0.19	0.19	0.23	0.24
	5	0.20	0.22	0.22	0.25	0.27	0.27	0.28	0.28	0.26	0.28	0.31	0.34	0.22	0.23	0.26	0.26
0% (VacSat)	1	0.24	0.26	0.26	0.30	0.30	0.30	0.34	0.35	0.38	0.39	0.44	0.47	0.29	0.30	0.32	0.31
	2	0.28	0.28	0.29	0.30	0.31	0.32	0.34	0.35	0.43	0.44	0.47	0.48	0.27	0.27	0.25	0.22
	3	0.32	0.31	0.33	0.34	0.36	0.38	0.41	0.43	0.45	0.47	0.50	0.52	0.21	0.21	0.25	0.27
	4	0.27	0.26	0.28	0.30	0.33	0.33	0.35	0.35	0.40	0.41	0.44	0.46	0.28	0.28	0.31	0.31
	5	0.29	0.28	0.30	0.31	0.33	0.33	0.36	0.37	0.46	0.48	0.52	0.52	0.29	0.28	0.28	0.23
2% Cem (MC)	1	0.15	0.15	0.16	0.17	0.16	0.17	0.20	0.20	0.18	0.19	0.22	0.25	0.14	0.16	0.20	0.21
	2	0.16	0.16	0.21	0.21	0.20	0.20	0.24	0.25	0.22	0.24	0.30	0.31	0.20	0.22	0.26	0.28
	3	0.18	0.17	0.20	0.22	0.22	0.22	0.25	0.25	0.26	0.27	0.30	0.32	0.20	0.22	0.25	0.25
	4	0.07	0.11	0.11	0.12	0.17	0.17	0.19	0.20	0.17	0.19	0.20	0.22	0.13	0.14	0.15	0.16
	5	0.15	0.17	0.20	0.18	0.19	0.22	0.24	0.25	0.22	0.24	0.30	0.28	0.19	0.20	0.26	0.29
2% Cem (VacSat)	1	0.17	0.19	0.24	0.25	0.22	0.23	0.25	0.28	0.26	0.28	0.31	0.35	0.21	0.21	0.25	0.27
	2	0.18	0.19	0.20	0.21	0.20	0.22	0.25	0.27	0.23	0.24	0.30	0.31	0.19	0.20	0.22	0.25
	3	0.20	0.20	0.19	0.23	0.21	0.23	0.25	0.24	0.22	0.23	0.26	0.28	0.19	0.21	0.23	0.22
	4	0.18	0.18	0.20	0.20	0.21	0.19	0.20	0.22	0.23	0.24	0.26	0.29	0.19	0.20	0.20	0.20
	5	0.20	0.25	0.26	0.26	0.27	0.27	0.29	0.32	0.27	0.30	0.33	0.36	0.24	0.24	0.28	0.29
2% SS-1 (MC)	1	0.26	0.27	0.29	0.29	0.33	0.33	0.34	0.35	0.31	0.34	0.41	0.44	0.31	0.32	0.37	0.38
	2	0.23	0.25	0.27	0.25	0.26	0.29	0.32	0.33	0.36	0.38	0.43	0.45	0.34	0.35	0.38	0.38
	3	0.24	0.23	0.28	0.27	0.27	0.28	0.32	0.31	0.32	0.33	0.37	0.41	0.32	0.32	0.35	0.37
	4	0.26	0.25	0.27	0.28	0.32	0.31	0.34	0.35	0.32	0.35	0.40	0.45	0.33	0.34	0.37	0.38
	5	0.25	0.26	0.28	0.30	0.28	0.30	0.34	0.36	0.33	0.35	0.40	0.42	0.31	0.32	0.36	0.36
2% SS-1 (VacSat)	1	0.46	0.46	0.52	0.53	0.47	0.49	0.55	0.58	0.54	0.57	0.67	-	-	-	-	-
	2	0.39	0.40	0.45	0.46	0.47	0.48	0.51	0.52	0.59	0.63	0.75	-	-	-	-	-
	3	0.38	0.37	0.41	0.42	0.43	0.44	0.48	0.49	0.48	0.50	0.56	0.61	0.40	0.42	0.04	0.50
	4	0.48	0.48	0.54	0.55	0.53	0.55	0.60	0.62	0.62	0.67	0.70	-	-	-	-	-
	5	0.38	0.40	0.43	0.43	0.43	0.44	0.47	0.49	0.49	0.53	0.59	0.63	-	-	-	-
2% Cem/SS-1 (MC)	1	0.20	0.21	0.26	0.25	0.28	0.26	0.28	0.30	0.27	0.28	0.31	0.33	0.24	0.27	0.29	0.29
	2	0.20	0.21	0.24	0.23	0.27	0.28	0.29	0.30	0.27	0.29	0.35	0.38	0.23	0.25	0.28	0.30
	3	0.19	0.22	0.24	0.26	0.25	0.26	0.29	0.31	0.26	0.28	0.33	0.34	0.27	0.28	0.31	0.32
	4	0.21	0.25	0.25	0.25	0.23	0.25	0.28	0.28	0.25	0.27	0.32	0.34	0.24	0.25	0.29	0.30
	5	0.20	0.21	0.25	0.27	0.26	0.25	0.27	0.29	0.27	0.29	0.32	0.34	0.21	0.24	0.28	0.29
2% Cem/SS-1 (VacSat)	1	0.26	0.28	0.27	0.28	0.30	0.30	0.32	0.33	0.35	0.34	0.38	0.43	0.21	0.20	0.23	0.22
	2	0.27	0.28	0.39	0.28	0.28	0.30	0.34	0.34	0.33	0.35	0.41	0.44	0.25	0.26	0.29	0.29
	3	0.26	0.28	0.33	0.34	0.31	0.32	0.35	0.36	0.35	0.36	0.40	0.44	0.31	0.33	0.35	0.33
	4	0.22	0.24	0.30	0.29	0.29	0.28	0.31	0.32	0.29	0.31	0.35	0.39	0.26	0.26	0.31	0.30
	5	0.24	0.26	0.27	0.29	0.28	0.28	0.31	0.32	0.30	0.30	0.35	0.39	0.22	0.24	0.27	0.28

Table B.5 2009 GW RAP Phase Angle across All Stress States

GW RAP with Stabilizer	Sample	Phase Angle (degrees)															
		Low Stress State				Medium Stress State				High Stress State				Fully Reversed Stress State			
		10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz
0% (MC)	1	14.4	13.9	12.6	12.0	14.7	13.3	12.9	12.9	15.7	14.5	14.2	14.1	16.9	15.8	15.7	15.8
	2	13.3	11.6	11.5	11.5	14.3	13.1	12.5	12.6	15.5	14.5	13.9	14.0	16.4	15.6	15.4	15.6
	3	12.9	11.6	10.5	11.5	14.0	12.8	12.5	12.2	15.2	14.0	13.8	13.7	15.9	14.9	14.8	14.8
	4	13.5	12.2	11.6	11.8	14.5	13.1	12.5	12.4	15.9	14.7	14.1	13.9	16.5	15.5	15.3	15.3
	5	13.1	12.1	10.3	10.6	13.9	12.5	12.0	11.8	15.2	13.9	13.4	13.4	16.0	15.1	15.0	14.8
0% (VacSat)	1	20.2	18.0	15.6	14.4	19.6	18.0	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2% Cem (MC)	1	11.3	10.1	9.7	10.0	12.6	11.6	11.0	10.7	13.3	12.1	11.8	11.9	14.0	12.6	12.5	12.9
	2	11.6	10.9	9.2	9.7	12.2	11.0	11.0	10.8	12.8	12.4	11.9	11.8	13.6	12.7	12.5	12.8
	3	10.5	8.7	8.9	9.7	11.9	9.2	10.2	10.6	12.3	11.5	11.6	11.6	12.3	11.9	11.4	11.8
	4	10.2	9.9	9.0	10.3	12.7	11.0	10.7	10.1	13.7	12.7	12.1	12.2	13.6	12.9	12.9	12.9
	5	12.3	10.6	9.2	9.8	12.6	11.6	11.0	10.8	13.6	12.5	12.1	12.3	13.7	13.1	12.5	12.9
2% Cem (VacSat)	1	15.0	13.6	12.6	12.4	15.7	14.3	12.9	12.7	16.8	15.2	14.3	13.9	18.8	17.2	16.4	15.5
	2	14.8	12.5	11.6	11.8	15.0	13.7	12.7	12.4	16.2	14.9	14.2	13.8	18.0	16.6	15.8	15.8
	3	13.3	12.8	11.2	11.3	14.4	13.0	12.0	11.9	15.6	14.5	13.5	13.5	16.7	15.5	15.0	14.4
	4	14.3	12.4	12.3	11.9	14.9	13.5	12.1	12.1	15.9	14.6	13.6	13.7	17.7	16.5	15.9	15.6
	5	14.7	13.1	11.9	11.1	14.9	13.1	12.1	11.9	16.2	14.4	13.6	13.4	17.1	16.3	15.4	15.0
2% SS-1 (MC)	1	17.9	16.9	15.6	15.3	19.5	18.3	16.9	16.2	21.3	20.0	18.7	18.0	22.7	21.7	21.4	21.1
	2	18.3	17.1	15.8	16.0	19.4	18.3	17.2	16.5	21.5	19.8	18.7	18.1	22.6	22.0	21.5	21.1
	3	18.4	16.7	15.7	15.3	19.5	18.1	16.8	16.6	21.3	20.0	18.8	18.2	22.6	21.7	21.2	20.9
	4	19.0	17.2	15.9	15.0	19.7	18.2	16.5	15.8	21.7	20.0	18.4	17.8	22.8	22.0	21.4	21.0
	5	18.7	17.6	15.7	15.0	19.4	18.1	16.8	16.2	21.1	19.8	18.2	17.6	22.5	21.7	21.3	21.0
2% SS-1 (VacSat)	1	22.3	19.6	17.4	6.0	21.6	19.6	17.0	15.7	21.7	19.9	18.5	-	-	-	-	-
	2	21.5	19.2	15.9	14.8	20.6	18.7	16.1	15.0	-	-	-	-	-	-	-	-
	3	20.8	18.4	16.4	14.8	21.0	19.0	17.1	17.0	-	-	-	-	-	-	-	-
	4	22.0	19.7	16.3	15.0	21.1	19.1	16.0	15.1	21.6	19.4	20.1	-	-	-	-	-
	5	23.4	20.8	18.0	16.5	21.1	19.4	17.1	17.2	-	-	-	-	-	-	-	-
2% Cem/SS-1 (MC)	1	14.9	14.2	13.5	12.5	16.0	14.6	14.1	13.0	17.0	15.8	15.3	15.1	17.1	16.4	16.2	16.3
	2	13.3	13.4	12.5	12.1	15.3	14.1	13.3	12.9	17.0	15.4	14.9	14.9	17.7	16.5	16.5	16.4
	3	12.8	12.6	11.5	10.9	14.8	13.8	13.0	12.5	16.7	15.4	14.4	14.5	16.8	15.8	15.6	15.7
	4	14.4	13.0	12.0	11.8	15.6	14.4	13.2	13.0	17.0	16.0	14.9	15.2	17.4	16.8	16.5	16.4
	5	15.0	13.0	12.6	11.8	15.3	14.5	13.7	13.4	18.0	16.8	15.7	15.7	18.3	17.4	17.2	17.1
2% Cem/SS-1 (VacSat)	1	17.2	16.0	13.3	13.5	18.5	17.3	15.4	15.0	20.3	19.0	17.1	16.6	23.0	21.7	21.0	20.7
	2	18.0	15.4	14.4	13.7	18.1	16.7	15.0	14.5	19.8	18.3	16.9	16.6	22.8	21.7	20.9	20.6
	3	17.8	15.8	14.1	13.4	18.5	16.6	15.0	14.6	21.4	19.1	17.5	17.1	25.1	22.9	21.2	20.7
	4	18.8	17.1	15.3	14.7	19.6	18.0	16.0	15.3	20.7	19.1	17.0	16.6	24.5	23.2	20.0	17.6
	5	18.5	17.4	14.3	14.7	19.6	17.8	16.3	15.5	20.9	19.3	17.6	17.0	25.0	23.3	19.8	17.7

Table B.6 2009 OGBC RAP Phase Angle across All Stress States

OGBC RAP with Stabilizer	Sample	Phase Angle (degrees)															
		Low Stress State				Medium Stress State				High Stress State				Fully Reversed Stress State			
		10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz
0% (MC)	1	17.2	17.2	17.2	17.3	18.9	18.0	17.8	17.8	19.5	18.2	19.1	19.1	19.7	19.4	21.2	21.3
	2	17.2	16.2	16.4	16.0	18.2	17.1	17.7	17.3	19.0	18.0	18.6	18.3	19.1	19.1	20.5	21.1
	3	18.2	17.2	16.8	17.0	18.5	17.7	17.3	17.3	19.7	18.9	18.7	18.5	19.8	19.9	21.0	21.3
	4	17.9	17.2	17.1	16.6	19.2	17.7	17.0	17.2	19.8	18.5	18.6	18.7	20.5	19.9	20.9	20.9
	5	18.2	17.4	17.0	17.5	18.8	18.0	17.5	17.6	20.1	18.8	18.8	18.8	21.1	20.6	21.5	21.5
0% (VacSat)	1	20.9	19.5	18.7	17.6	21.2	19.4	18.4	17.7	21.5	20.4	18.9	18.5	24.5	24.2	23.8	22.3
	2	22.2	20.3	18.3	17.6	21.3	19.6	18.4	17.5	21.5	19.6	18.3	17.7	25.5	24.7	22.7	20.1
	3	21.6	20.4	18.1	17.9	22.1	20.7	18.8	18.2	22.4	20.7	19.4	18.8	26.9	24.9	22.5	20.3
	4	21.8	20.1	17.5	17.0	21.1	19.6	17.9	17.5	21.9	20.1	18.8	18.3	25.0	24.1	24.0	23.7
	5	20.8	19.9	17.6	17.3	21.0	19.9	18.2	17.5	21.4	19.8	18.7	18.1	25.1	24.4	23.3	20.8
2% Cem (MC)	1	15.5	13.7	15.0	14.2	16.0	15.5	15.8	15.7	17.4	16.4	16.8	17.0	17.6	17.3	18.2	18.7
	2	13.6	13.6	14.1	13.2	15.3	14.9	14.9	15.3	16.6	16.1	16.3	16.8	16.8	17.0	18.1	18.5
	3	15.5	14.7	14.3	15.8	16.5	15.6	15.2	15.5	17.7	16.9	17.1	17.0	17.9	17.2	18.6	18.8
	4	13.4	13.6	13.2	13.4	15.7	14.5	15.1	14.7	16.9	15.9	15.9	16.5	16.6	16.6	17.6	18.0
	5	15.3	15.1	13.5	14.7	15.8	15.0	15.2	15.1	17.6	17.0	16.8	16.7	17.6	17.1	18.3	18.7
2% Cem (VacSat)	1	17.3	15.8	16.3	16.1	17.8	17.0	16.2	16.8	19.9	18.7	18.2	17.8	20.2	20.0	20.6	21.1
	2	17.8	16.0	15.0	16.6	19.2	18.0	17.0	17.0	19.4	18.3	17.9	17.9	20.5	19.8	20.3	20.3
	3	17.5	16.0	16.4	15.2	17.8	17.0	16.2	16.2	19.0	17.9	17.4	17.2	20.2	19.4	19.9	19.8
	4	17.0	15.8	15.2	15.1	18.0	16.9	15.9	15.5	18.5	17.6	17.4	17.1	20.1	19.3	19.2	19.5
	5	18.3	16.9	14.9	14.9	18.7	17.5	16.4	16.5	18.5	18.4	17.4	17.5	20.2	20.0	20.0	20.1
2% SS-1 (MC)	1	22.0	21.1	20.2	18.7	22.9	21.9	20.3	19.9	24.2	23.1	22.0	21.3	25.9	25.8	26.3	26.3
	2	22.2	21.8	20.0	18.7	23.0	21.5	20.2	19.3	24.3	22.8	21.4	21.0	26.5	26.7	26.3	25.9
	3	22.1	21.1	20.7	19.6	22.8	21.7	20.8	19.5	24.8	23.1	21.8	21.4	28.0	27.1	27.0	26.6
	4	23.6	21.9	19.6	18.9	23.5	21.8	19.7	19.2	25.2	23.4	21.6	21.2	27.8	27.1	26.6	26.0
	5	23.1	21.5	21.0	20.0	23.4	21.5	20.6	20.1	24.9	23.5	22.4	21.8	27.0	27.2	27.4	27.3
2% SS-1 (VacSat)	1	27.7	26.0	23.0	22.3	24.9	23.4	21.8	21.1	24.7	22.9	21.7	-	-	-	-	-
	2	25.9	24.0	21.6	20.9	24.4	22.7	20.7	19.6	24.1	22.1	23.9	-	-	-	-	-
	3	26.1	24.2	22.0	20.7	24.9	23.3	21.0	20.1	24.5	22.8	21.1	20.5	30.2	29.5	29.2	28.4
	4	27.1	24.7	22.1	20.6	24.4	22.8	21.0	20.2	23.9	22.4	21.4	-	-	-	-	-
	5	28.0	25.5	22.7	21.1	24.7	23.3	21.0	20.3	24.3	22.5	21.4	22.1	-	-	-	-
2% Cem/SS-1 (MC)	1	17.9	16.7	17.6	16.2	19.0	18.3	18.5	17.6	20.6	19.9	19.9	19.9	21.1	21.3	22.0	22.1
	2	18.9	17.8	17.5	17.2	19.2	18.3	18.2	18.0	20.3	19.3	19.5	19.4	20.7	21.1	22.1	22.1
	3	17.9	16.6	17.2	17.5	19.5	18.6	18.0	18.6	20.9	20.1	20.1	20.1	22.4	21.9	22.3	22.5
	4	21.2	19.4	18.7	17.5	21.0	19.6	19.3	18.5	21.9	20.5	20.1	20.0	21.9	22.2	22.8	23.2
	5	18.5	18.9	17.7	16.9	19.5	18.8	18.6	18.1	21.2	20.4	20.0	19.8	22.5	22.1	22.8	22.7
2% Cem/SS-1 (VacSat)	1	23.2	20.7	20.7	20.4	23.2	21.6	20.4	19.8	23.7	22.1	21.3	20.9	25.4	23.9	22.1	20.4
	2	21.5	18.9	18.7	18.1	21.2	20.2	18.7	18.7	22.2	21.2	20.4	19.9	24.7	24.7	24.9	24.6
	3	22.1	21.3	19.1	18.9	22.8	21.7	20.4	19.9	24.4	22.5	21.5	20.9	26.4	26.0	26.0	23.9
	4	20.9	21.2	19.1	18.0	21.0	20.1	19.1	18.6	22.3	21.1	20.4	19.7	24.5	23.8	24.2	24.0
	5	20.9	20.2	19.3	18.6	21.9	20.2	19.3	18.2	23.1	21.9	20.0	19.7	25.1	24.4	24.5	24.5

Table B.7 2009 GW RAP Radial Microstrain across All Stress States

GW RAP with Stabilizer	Sample	Radial Microstrain															
		Low Stress State				Medium Stress State				High Stress State				Fully Reversed Stress State			
		10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz
0% (MC)	1	26	28	33	39	62	67	81	88	126	142	182	204	102	112	143	156
	2	21	23	28	33	54	58	73	78	126	139	185	212	103	112	145	162
	3	22	22	28	25	53	58	68	75	120	132	171	194	94	100	133	149
	4	27	30	33	37	69	72	88	95	158	175	225	248	124	139	172	189
	5	31	30	35	40	72	77	91	101	162	182	227	251	137	146	181	199
0% (VacSat)	1	203	217	270	275	444	501	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2% Cem (MC)	1	10	12	14	13	26	28	37	37	54	59	72	78	40	41	45	53
	2	12	10	12	16	32	33	36	41	55	60	76	82	43	50	58	68
	3	9	10	12	11	24	27	29	32	45	46	57	67	29	31	41	44
	4	9	12	13	12	24	24	30	35	48	52	64	77	36	37	50	52
	5	12	10	12	15	23	26	32	31	47	56	68	74	37	38	49	54
2% Cem (VacSat)	1	19	18	20	23	47	49	59	69	100	108	147	167	84	98	127	154
	2	15	17	18	22	40	43	53	56	90	100	133	153	70	76	101	112
	3	9	10	10	13	30	29	41	38	68	77	96	113	50	55	73	79
	4	13	14	21	20	34	36	43	50	71	86	118	139	75	82	107	121
	5	14	15	20	17	34	38	49	50	75	76	107	124	58	68	90	96
2% SS-1 (MC)	1	33	35	46	49	70	83	110	123	135	158	235	274	113	136	202	227
	2	34	33	44	49	68	86	111	124	137	165	236	276	113	134	197	232
	3	26	31	41	44	63	75	100	114	127	153	227	263	100	121	178	204
	4	28	32	43	42	71	79	110	120	134	158	232	269	112	140	214	244
	5	28	29	38	45	62	72	97	113	127	151	227	263	96	121	178	208
2% SS-1 (VacSat)	1	183	177	176	158	313	364	434	419	603	702	922	-	-	-	-	-
	2	108	117	129	123	210	233	285	292	-	-	-	-	-	-	-	-
	3	84	89	113	125	236	274	380	429	-	-	-	-	-	-	-	-
	4	78	81	91	98	167	189	234	250	463	532	775	-	-	-	-	-
	5	156	182	241	275	329	377	512	587	-	-	-	-	-	-	-	-
2% Cem/SS-1 (MC)	1	21	21	26	27	47	54	68	72	108	121	160	176	79	86	113	122
	2	12	12	19	17	36	38	49	55	83	97	136	157	60	67	89	96
	3	15	16	17	20	40	40	50	52	98	108	138	156	68	75	99	106
	4	23	23	32	30	58	64	78	87	128	143	190	219	109	120	156	174
	5	15	14	21	22	47	49	62	69	105	121	169	195	76	91	125	143
2% Cem/SS-1 (VacSat)	1	49	57	65	69	117	134	175	211	321	357	453	492	158	177	252	303
	2	36	41	49	49	83	92	118	132	247	290	398	452	168	186	258	296
	3	25	26	32	37	66	72	96	114	211	249	355	415	198	222	303	333
	4	45	50	64	73	107	121	154	183	254	300	398	462	283	336	621	898
	5	33	42	45	52	87	115	163	184	257	307	418	477	280	348	649	755

Table B.8 2009 OGBC RAP Radial Microstrain across All Stress States

OGBC RAP with Stabilizer	Sample	Radial Microstrain															
		Low Stress State				Medium Stress State				High Stress State				Fully Reversed Stress State			
		10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz
0% (MC)	1	21	22	28	34	40	44	66	75	67	79	124	152	53	64	99	117
	2	15	21	28	27	38	43	56	67	70	74	114	136	48	60	93	102
	3	18	21	27	33	42	49	65	75	66	84	126	147	60	65	104	127
	4	17	19	26	30	39	43	65	75	66	78	123	151	52	57	93	110
	5	18	22	27	33	44	51	68	73	69	84	123	151	52	60	92	106
0% (VacSat)	1	29	33	43	54	67	76	115	130	148	174	258	303	129	160	275	355
	2	35	40	53	60	75	90	125	140	188	216	299	343	158	187	315	399
	3	45	47	65	74	95	115	162	188	203	240	334	383	317	374	721	1022
	4	35	37	50	57	82	93	128	141	177	203	284	329	136	158	257	316
	5	35	38	52	60	77	90	126	144	196	240	328	353	157	180	323	440
2% Cem (MC)	1	14	15	19	20	25	30	43	47	47	55	79	98	34	43	67	78
	2	15	16	23	24	33	36	52	57	54	65	101	116	44	55	83	99
	3	16	15	21	25	33	36	52	54	68	77	109	127	47	57	82	94
	4	5	10	12	13	26	29	37	43	41	50	69	81	30	35	49	56
	5	14	16	23	22	32	40	54	59	58	69	110	136	47	54	93	114
2% Cem (VacSat)	1	15	18	27	30	34	40	56	68	71	84	123	153	55	60	100	121
	2	17	19	24	27	36	42	61	71	66	79	124	145	54	65	99	127
	3	18	20	21	28	34	41	56	59	62	73	106	128	51	62	91	99
	4	16	17	22	22	32	33	43	51	62	69	96	120	48	55	76	85
	5	19	25	31	33	44	50	68	79	76	94	138	163	64	73	116	137
2% SS-1 (MC)	1	28	32	45	49	64	74	105	121	97	123	206	250	81	100	175	215
	2	24	28	41	42	51	66	99	112	113	140	222	260	93	112	186	222
	3	23	25	40	43	51	62	95	105	97	118	186	238	83	100	171	213
	4	31	33	46	51	69	77	113	132	111	141	227	285	99	120	202	239
	5	28	33	44	52	57	70	105	125	105	130	208	252	84	103	177	213
2% SS-1 (VacSat)	1	80	93	144	167	143	175	275	330	263	331	536	-	-	-	-	-
	2	64	76	117	135	136	164	242	277	296	369	622	-	-	-	-	-
	3	61	69	102	119	124	153	228	265	229	278	430	532	218	273	43	582
	4	110	126	190	212	211	251	369	418	391	489	714	-	-	-	-	-
	5	65	76	111	121	125	150	219	255	236	299	459	565	-	-	-	-
2% Cem/SS-1 (MC)	1	18	20	31	31	43	47	64	75	66	78	115	139	49	62	92	106
	2	19	20	29	29	43	50	65	77	68	83	132	161	49	60	91	112
	3	17	21	28	31	37	45	63	74	61	75	119	140	53	63	100	119
	4	18	24	31	32	36	46	66	73	61	76	120	147	51	61	102	121
	5	18	20	29	33	40	44	62	72	64	79	119	145	42	57	93	111
2% Cem/SS-1 (VacSat)	1	28	33	43	48	54	65	96	111	104	123	193	247	78	104	200	271
	2	24	28	39	41	49	61	90	102	97	118	192	234	69	86	139	169
	3	25	29	46	52	54	64	98	114	98	118	187	234	85	109	189	249
	4	20	24	38	41	46	53	79	89	78	95	149	187	65	76	131	153
	5	21	25	34	41	46	54	78	91	81	95	156	194	60	77	128	160

APPENDIX C. GREEN STREET TEST SECTION INFORMATION

TEST SECTION LAYOUT AND STRUCTURAL DESIGN

The City of Saskatoon (COS) implemented the "Green Street" Infrastructure Program in early 2009. The main objective of the program was to investigate the ability to reclaim and recycle asphalt and concrete and to reuse it as structural materials in road rehabilitation test sections.

This chapter contains the test section layout, pre construction visual condition survey, and reclaimed asphalt pavement systems constructed for test sections including Marquis Drive and 8th Street. The same construction process was used for both Marquis Drive and 8th Street and will be explained and detailed using photos taken during the construction process on Marquis Drive.

The City of Saskatoon and its engineers were responsible for test section design, construction, consultant and contractors, and pre and post construction falling weight deflectometer testing. Falling weight deflectometer testing was conducted by PSI Technologies Inc. No information with regards to surface distress measurements including International Roughness Index and cracking was provided by the City of Saskatoon. Also, no information with regards to maintenance and repair history was provided by the City. Therefore, this information is not provided for Marquis Drive and 8th Street test sections.

Marquis Drive

The construction limits of Marquis Drive are pictured in Figure C.1. The construction limits of Marquis Drive were from the intersection of Thatcher Avenue at km 0.000, east to the intersection of Idylwyld Drive at km 0.425, for the eastbound lanes only. The construction limits were divided at the west end of Marquis Drive (km 0.000 to Costco Entrance at km 0.175) and at the east end of Marquis Drive (km 0.175 to km 0.425) for different rehabilitation pavement structures.

Pre construction, the pavement structure of Marquis Drive was a hot mix asphalt concrete (HMAC) surface on a typical granular base structure. A pre construction photo of the pavement condition is illustrated in Figure C.2. The pre construction pavement condition of Marquis Drive had a HMAC surface that was intact with localized structural failures, rutting, localized potholes, and fatigue and longitudinal cracking. Marquis Drive is located within an industrial area of Saskatoon and provides access to the Costco shopping centre and is subject to heavy truck traffic. Structural failures were due to substructure moisture problems and heavy truck traffic.

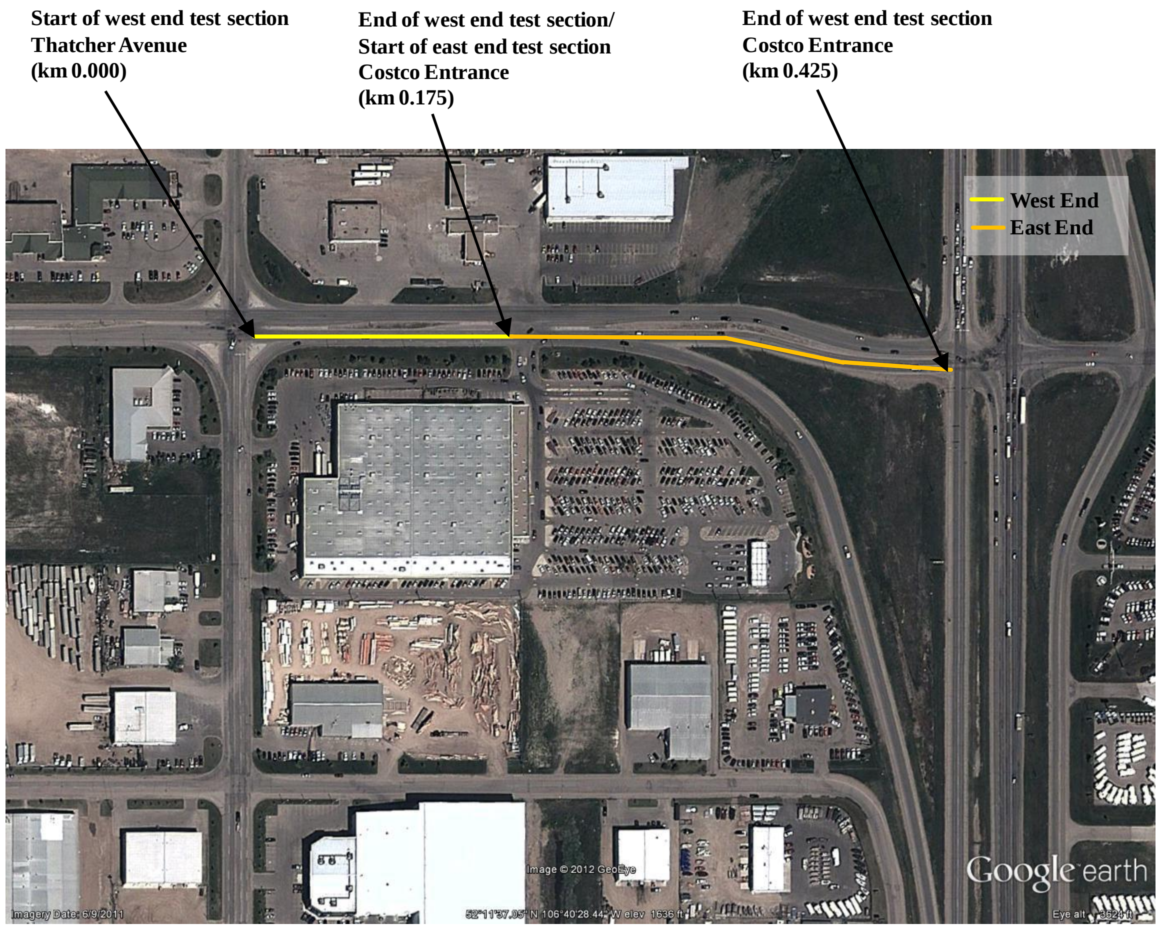


Figure C.1 Marquis Drive Construction Limits (image courtesy of Google maps)

The objective of the full depth rehabilitation of the eastbound lanes of Marquis Drive was to increase the load carrying capacity of the pavement structure by reclaiming and reusing *in situ* material in addition to using processed, stockpiled recycled materials from the COS. The reclaimed Portland cement concrete (PCC) drainage rock layer was crushed and processed in Saskatoon. The reclaimed asphalt pavement (RAP) layer contained *in situ* material obtained from rotomixing Marquis Drive during construction as well as crushed well graded (GW) RAP material from the COS stockpiles.

Figure C.2 Marquis Drive Pre Construction, Facing West (courtesy of PSI Technologies)

The objective of the full depth rehabilitation of the eastbound lanes of Marquis Drive was to increase the load carrying capacity of the pavement structure by reclaiming and reusing *in situ* material in addition to using processed, stockpiled recycled materials from the COS. The reclaimed Portland cement concrete (PCC) drainage rock layer was crushed and processed in Saskatoon. The reclaimed asphalt pavement (RAP) layer contained *in situ* material obtained from rotomixing Marquis Drive during construction as well as crushed well graded (GW) RAP material from the COS stockpiles.

Figure C.3 illustrates the post construction design cross sections for Marquis Drive. The design was conducted by the City. The west end of Marquis Drive (km 0.000 to Costco Entrance at km 0.175) was constructed with a 250 mm reclaimed Portland cement concrete (PCC) coarse drainage rock layer and weeping tile for substructure drainage, as the Costco entrance was noticeably wet during construction. A 250 mm layer of RAP/base material was placed on top of the PCC drainage layer and the top 100 mm of RAP was SS-1 emulsion stabilized. The east end of Marquis Drive (km 0.175 to km 0.425) was constructed with 250 mm reclaimed PCC (minus 19 mm, well graded) with no weeping tile. A 250 mm layer of RAP/base material was placed on top of the PCC drainage layer and the top 100 mm of RAP was SS-1 emulsion stabilized. Both the west and east ends of Marquis Drive were surfaced with 100 mm of hot mix asphalt concrete (HMAC) placed in two lifts.

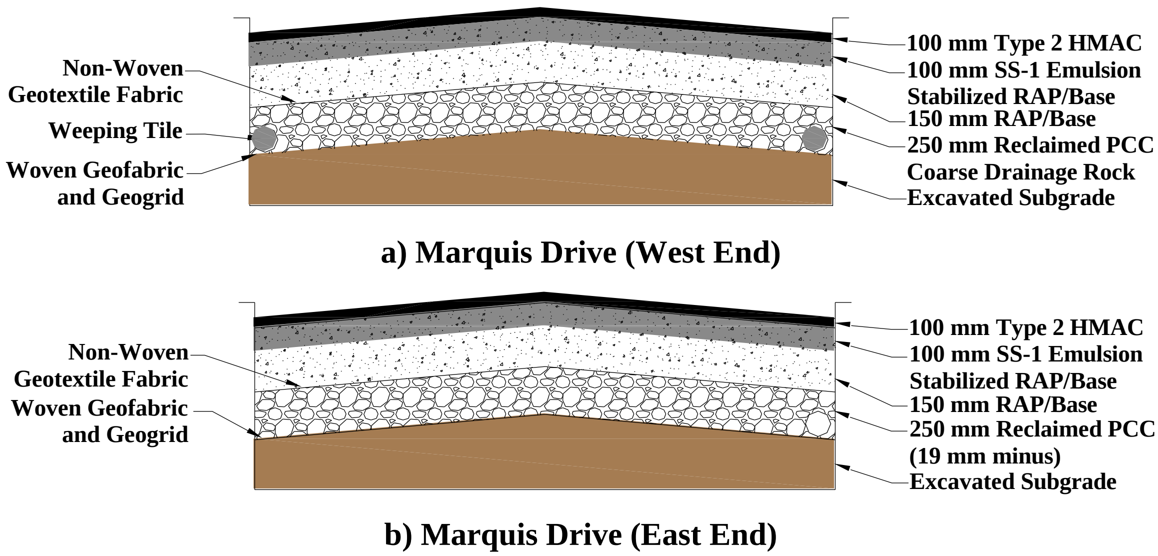


Figure C.3 Rehabilitated Cross Sections of Marquis Drive

To maximize use of RAP material, *in situ* granular base material and HMAC was milled and rotomixed in-place and placed as part of the rehabilitated structure on Marquis Drive. Crushed well graded (GW) RAP material from the COS stockpiles was used to achieve a total depth of 250 mm RAP material as a base layer.

8th Street East

The construction limits of 8th Street East are illustrated in Figure C.4. The construction limits of the westbound lanes of 8th Street East were from the intersection of Boychuk Drive, west km 0.540. 8th Street is an arterial road and serves as a connector route for the east side of Saskatoon. 8th Street East is composed of a right turn lane, a driving lane, and a passing lane (median lane). The right turn lane was rehabilitated with a different structure than the driving lane and passing lane.

End of test section
(km 0.540)

Start of test section
Boychuk Drive
(km 0.000)

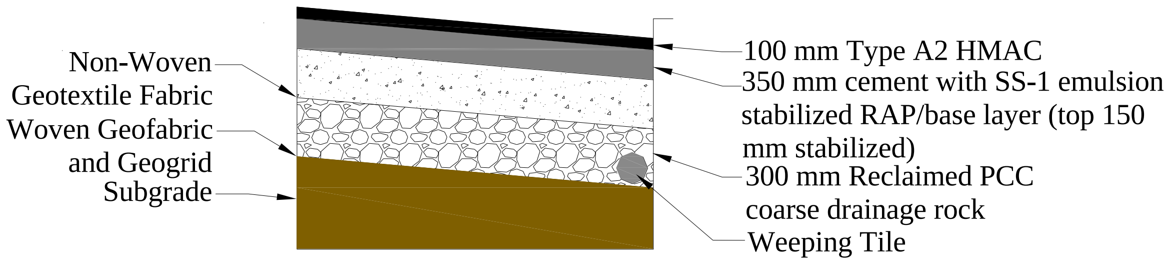
Figure C.4 8th Street Control Limits (image courtesy of Google maps)

Figure C.5 Localized Structural Failures, Potholes, and Moderate Rutting on 8th Street Pre Construction (courtesy of PSI Technologies)

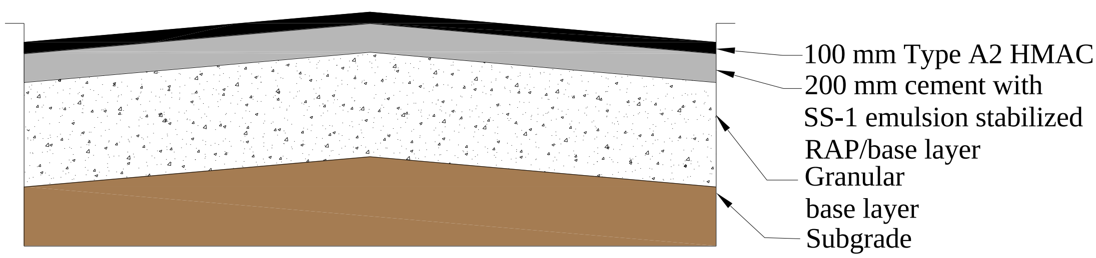
Pre construction, the passing and driving lanes of 8th Street were comprised of an HMAC surface on a granular base structure. The right turn lane was comprised of a HMAC surface placed on a structure consisting of granular base and topsoil. A typical pre construction photo of the pavement condition is illustrated in Figure C.5.

The pre construction pavement condition of 8th Street had a HMAC surface that was intact with localized structural failures, rutting, localized potholes, and fatigue cracking. Pre construction, the right hand turning lane of 8th Street had the poorest surface condition due to increased moisture in its substructure. This was due to its construction on some topsoil and increased moisture from the grass curbside.

Figure C.6 illustrates the post construction cross sections of 8th Street East. The design was conducted by the City. The rehabilitation of 8th Street consisted of two pavement rehabilitation systems.



a) 8th Street Right Turn Lane Cross Section



b) 8th Street Driving Lane and Passing Lane Cross Section

Figure C.6 Rehabilitated Cross Sections of 8th Street East

Figure C.6 a) illustrates the rehabilitated cross section for the right turn lane of 8th Street. The right turn lane had moisture problems pre construction and a drainage layer was installed in this lane only. The rehabilitated cross section of the right turn lane consisted of a woven geotextile placed on the subgrade to separate the crushed PCC drainage layer, geotextile and a crushed GW RAP base layer placed on top of the reclaimed PCC drainage layer. City of Saskatoon offsite impact crushed RAP and PCC materials were used in the base layer and drainage system. Figure C.6 b) illustrates the rehabilitated cross section for the driving and passing lanes of 8th Street. The existing

HMAC surface and top 200 mm of granular base were milled, rotomixed and compacted. Additional crushed GW RAP materials were added to top up the depth of RAP base layer. The top 150 mm of the RAP base layer in the right turn lane, driving lane, and passing lane (median lane) was stabilized with one percent cement with one percent SS-1 emulsion. The entire 8th Street test section was surfaced with HMAC.

TEST SECTION CONSTRUCTION PROCESS

Marquis Drive and 8th Street test sections were rehabilitated during the construction season of 2009. Marquis Drive was constructed in May 2009 and 8th Street East was constructed in July 2009. The same construction process was used for both Marquis Drive and 8th Street and is explained using photos taken during Marquis Drive construction. The City of Saskatoon contracted the construction operations and was responsible for project management throughout construction. Separate contractors were used for milling the HMAC surface, full depth construction, material haul, and HMAC placement. Traditional construction equipment was used for the reconstruction of the test sections. No specialized equipment was used for hauling, placement, or compaction.

Construction began on Marquis Drive and 8th Street East by milling the existing HMAC and a portion of the granular base material to a depth of 150 mm. The milling process is illustrated in Figure C.7. Milling the existing HMAC and rotomixing with *in situ* granular base material removed the existing, distressed asphalt mat and mixed it homogeneously with a portion of the underlying granular base material. This material was stockpiled and the road structure was excavated to a depth ranging from 0.6 m to 0.8 m, depending on the design requirements. Figure C.8 illustrates the excavated structure and placement of weeping tile.

Weeping tile was placed on top of the subgrade, within the PCC rock drainage layer, when a drainage layer was required. Weeping tile was tied into the COS storm sewer system. As part of the drainage layer, woven geofabric and geogrid were placed on the excavated subgrade (Figure C.9). In the case of Marquis Drive, the weeping tile was placed in the layer of PCC drainage rock, against the curb and tied into the storm sewer, as illustrated in Figure C.9 and Figure C.10.

Figure C.7 Pre-Milling and Reclamation of HMAC and Granular Base Materials (courtesy of PSI Technologies)

Figure C.8 Excavated Road Structure and Placement of Weeping Tile on Subgrade (courtesy of COS)

Figure C.9 Woven Geofabric and Geogrid on Subgrade (courtesy of COS)

Figure C.10 Weeping Tile tied in to the Storm Sewer (courtesy of COS)

Figure C.11 illustrates the placement of impact crushed COS PCC drainage rock on the geogrid and woven geotextile. Impact crushed PCC drainage rock was processed, crushed, and stockpiled for use in "Green Street" test sections, such as Marquis Drive and

8th Street, as a drainage layer. Figure C.12 illustrates the placement of geotextile to separate the PCC drainage layer and the RAP base layer.

For both test sections, the milled HMAC and rotomixed granular material was hauled offsite and stockpiled. For both test sections, this RAP material was reused and placed as a base layer in the rehabilitated road structure following installation of a drainage layer (when used in design). Additional crushed GW RAP material was used to meet design requirements for depth of base layer (to "top it off"). Figure C.13 illustrates the placement of crushed GW RAP materials as a base layer.

After placement of the base layer, the RAP materials were stabilized to the design depth with cement and/or SS-1 emulsion. The crushed RAP material layer on Marquis Drive was stabilized to a depth of 100 mm with two percent SS-1 emulsion. The crushed RAP material on 8th Street East was stabilized to a depth of 150 mm with one percent cement with one percent SS-1 emulsion.

Figure C.14 illustrates the application of SS-1 emulsion to the crushed RAP base layer. Figure C.15 illustrates rotomixing the SS-1 emulsion with the crushed RAP base layer to uniformly blend the top 100 mm of RAP base layer. In the case of 8th Street, the cement was applied to the RAP base layer and rotomixed to uniformly blend to a depth of 150 mm. This was followed by the application of SS-1 emulsion to the cement-stabilized RAP base layer, which was then blended through the top 150 mm of RAP base layer.

Following cement and/or SS-1 emulsion stabilization, the RAP base layer was compacted using pneumatic rollers to achieve a smooth, compacted surface. Figure 0.16 illustrates the smooth, finished, compacted surface of the SS-1 emulsion stabilized RAP base layer on Marquis Drive. All test sections were paved with 100 mm of HMAC. Figure C.17 illustrates the final HMAC surface.

Figure C.11 Placement of PCC Drainage Rock (courtesy of COS)

Figure C.12 Placement of Non-Woven Geotextile Fabric (courtesy of COS)

Figure C.13 Placement of Crushed GW RAP Materials (courtesy of COS)

Figure C.14 Application of SS-1 Emulsion to RAP Base Layer (courtesy of COS)

Figure C.15 Rotomixing SS-1 Emulsion and RAP Material (courtesy of COS)

Figure 0.16 Finished Compacted RAP Base Layer (courtesy of COS)

Figure C.17 Finished Hot Mix Asphalt Concrete Surface (courtesy of COS)

FALLING WEIGHT DEFLECTOMETER TESTING

The City of Saskatoon employs structural asset management and falling weight deflectometer (FWD) measurements in its asset management system. The City uses FWD measurements to complement its visual condition surveys to make decisions with regards to road preservation strategies, traffic detours, and to plan bus routes (Berthelot et al 2010e, Prang et al. 2007). FWD testing for COS was conducted by PSI Technologies Inc.; the data used herein is used with permission from PSI Technologies. The falling weight deflectometer is a non-destructive technology that collects peak surface deflection across a load spectra of typical commercial truck traffic loadings (Berthelot et al. 2008c). The falling weight deflectometer is capable of assessing the structural integrity of a road structure to a depth greater than one meter (Noureldin et al. 2003). The City specifies that falling weight deflectometer measurements are taken every 30 m in one direction in inner wheelpaths and outer wheelpaths of each lane. Testing is conducted under primary legal load weight limits of 44.6 kN.

Falling weight deflectometer testing was conducted pre and post construction for all "Green Street" test sections. The purpose of pre construction FWD testing is to determine if there are any weak sections or anomalies in the road structure. The purpose of post construction FWD testing is to validate the rehabilitated road structure. Peak surface deflections were measured on Marquis Drive and 8th Street East test sections using the FWD both pre construction and post construction in 2009. Peak surface deflections were also taken the following summer in 2010, one year post construction.

Table C.1 lists and Figure C.18 illustrates the HWD peak surface deflections at primary legal load weight limits. The error bars represent the 5th and 95th percentiles. A maximum peak surface deflection of 0.75 mm for COS arterial roads is represented by a red dash line.

Table C.1 HWD Surface Deflection at Primary Legal Load Weight Limits

	Marquis Drive (Eastbound Lanes)						8th Street East (Westbound Lanes)		
	West End (km 0.000 to km 0.175)			East End (km 0.175 to km 0.425)					
	Pre 2009	Post 2009	Post 2010	Pre 2009	Post 2009	Post 2010	Pre 2009	Post 2009	Post 2010
Average (mm)	1.85	0.55	0.55	1.77	0.52	0.51	0.93	0.73	0.48
Minimum (mm)	0.57	0.43	0.45	1.05	0.43	0.40	0.38	0.40	0.23
Maximum (mm)	4.00	0.75	0.72	2.11	0.63	0.66	2.54	1.16	0.82
Std.Dev. (mm)	0.97	0.09	0.09	0.26	0.06	0.08	0.32	0.18	0.17
COV (%)	53%	16%	16%	15%	11%	16%	34%	25%	36%
5th Percentile	0.59	0.45	0.45	1.34	0.44	0.41	0.58	0.49	0.26
95th Percentile	3.14	0.71	0.69	2.10	0.61	0.64	1.33	1.01	0.74

A total of 30 FWD measurements were taken on Marquis Drive during each testing occurrence; 12 FWD measurements were taken on the west end and 18 FWD measurements were taken on the east end. Pre construction, average peak deflections at primary weight limits were 1.85 mm and 1.77 mm on the west and east ends, respectively. Post construction, average peak deflections at primary weight limits reduced compared to pre construction average deflections. Average deflections in the west end of Marquis Drive reduced by 70 percent post construction. Average deflections in the east end of Marquis Drive reduced by 71 percent post construction. Peak surface deflections measured following construction in 2009 and one year later in 2010 were comparable.

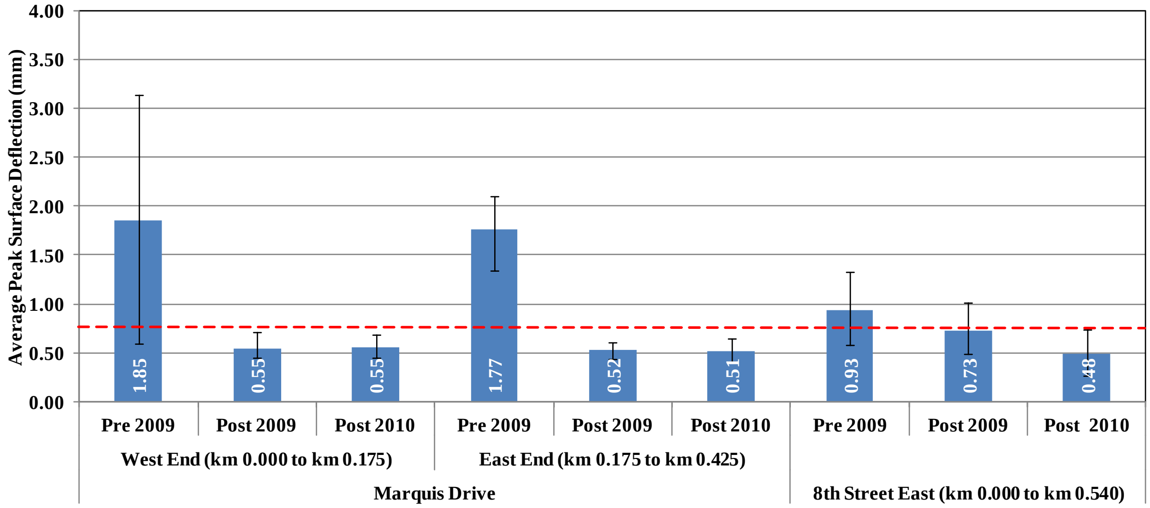


Figure C.18 Mean Peak Surface Deflections at Primary Legal Load Weight Limits (5^{th} and 95^{th} Percentile)

A total of 55 HWD measurements were taken on 8^{th} Street East during each testing occurrence. Pre construction, the average peak deflection at primary weight limits was 0.93 mm. Post construction, the average deflection reduced by 22 percent. A further reduction of 34 percent in average peak deflections was observed from post construction 2009 to post construction 2010 HWD measurements. It is hypothesized this further reduction in peak deflections is due to allowing the cement stabilization to cure.

Pre construction, both 8^{th} Street and Marquis Drive had average peak surface deflection at primary legal load weight limits greater than 0.75 mm. Post construction, the average deflections were reduced to 0.44 mm and 0.28 mm for 8^{th} Street and Marquis Drive, respectively.

ECONOMIC ANALYSIS

A comparison of the cost of constructing the 8th Street East and Marquis Drive test sections was conducted. This economic analysis was limited to the cost of acquiring and hauling aggregate material in 2009, the year of construction for the test sections included in this thesis. Cost of cement and/or emulsion stabilizers were not included. Life-cycle costs (LCC) were not calculated. The cost of crushed RAP material was compared to the cost of virgin granular base aggregate.

Table C.2 lists the unit cost per tonne for base aggregates discussed in this research. A unit cost range is used because the cost of aggregate is market-dependent and fluctuates depending on crushing and haul distance, as well as demand. Unit cost of virgin granular base aggregates was estimated to be $30 to $40 per tonne, following discussions with persons in the road construction industry. Unit cost of crushed RAP material was estimated to be $10 to $20 per tonne following discussion with persons in the road construction industry. The unit costs per tonne provided are listed as approximate ranges for the year the test sections included in this thesis were constructed.

Table C.2 Unit Costs of Base Aggregates

Base Aggregate or Stabilizer	Unit Cost (per tonne) - 2009
Virgin Granular Base Aggregate	$30 - $40
Crushed RAP Material	$10 - $20

In Saskatoon, the difference in unit cost between crushed virgin granular material and crushed RAP material is primarily due to length of haul (Berthelot et al. 2000a, 2009b). Had virgin granular base material been quarried and crushed outside of Saskatoon, the total haul distance may have been up to 80 kilometers roundtrip. The RAP material was crushed within COS limits and stockpiled at the City's east yard or reused onsite. For RAP material reclaimed and reused onsite, there is no haul distance. For RAP material crushed in Saskatoon, the haul distance from the stockpile yard to 8th Street is approximately three (3) kilometers and 19 kilometers to Marquis Drive.

Table C.3 lists the material quantities for Marquis Drive and 8th Street test sections. Material quantities were calculated in tonnes as this is the unit of measurement used in the road construction industry. To provide a direct comparison of the RAP material to the virgin base material, it was assumed that the depth of base layer would be the same for a virgin base layer as was constructed in the recycled base layer.

Table C.3 Base Layer Material Quantities for Test Sections

Test Section	Material Type	Material Quantity (Tonnes)
Marquis Drive West End	RAP Base Material	674
	Virgin Granular Base Material	643
Marquis Drive East End	RAP Base Material	963
	Virgin Granular Base Material	919
8th Street	RAP Base Material	4158
	Virgin Granular Base Material	3969

Figure C.19 illustrates and Table C.4 lists the average material costs for both RAP base and virgin granular base for the Marquis Drive and 8th Street test sections. The error bars represent the variation in cost, depending on the cost ranges presented in Table C.2. For both test sections, the virgin granular base is more costly than the RAP material for use as a base layer.

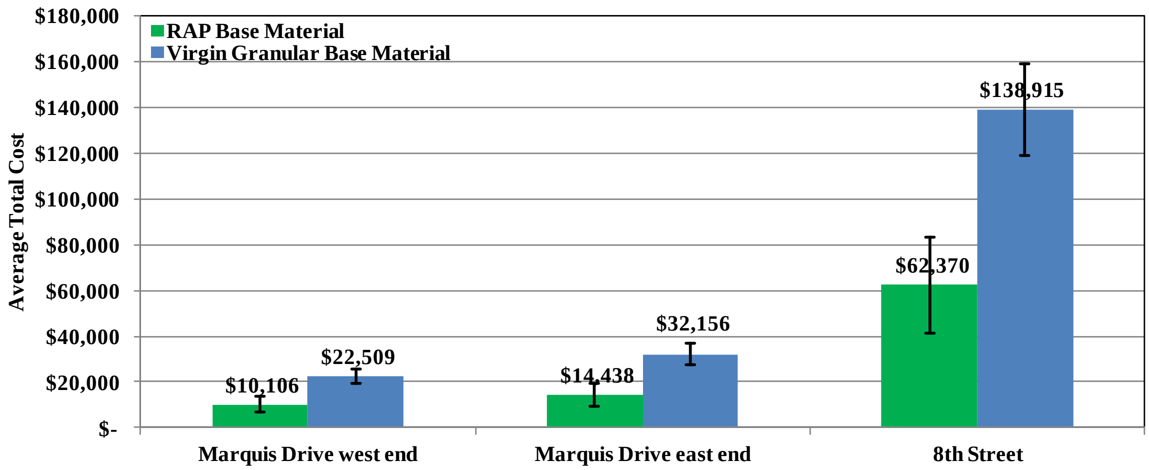


Figure C.19 Base Layer Total Material Costs for Test Sections

Table C.4 Base Layer Material Costs for Test Sections

Test Section	Material Type	Total Cost Range		
Marquis Drive West End	RAP Base Material	$ 6,736	to	$ 13,475
	Virgin Granular Base Material	$ 19,294	to	$ 25,725
Marquis Drive East End	RAP Base Material	$ 9,625	to	$ 19,250
	Virgin Granular Base Material	$ 27,563	to	$ 36,750
8th Street	RAP Base Material	$ 41,580	to	$ 83,160
	Virgin Granular Base Material	$119,070	to	$158,760

Based on the unit costs listed in Table C.2, the test section base layers constructed with RAP material cost approximately 48 percent to 65 percent less than conventional virgin base material counterparts. Had the test sections been constructed with virgin base material in lieu of RAP material, the costs would have increased. For example, had 8th Street been reconstructed using virgin granular base material, the cost would have increased by at least $75,000. Constructing the section of 8th Street with RAP material saved the COS at least $75,000.

SUMMARY

Test sections of Marquis Drive and 8th Street East were reconstruction with RAP base layers stabilization with SS-1 emulsion and one percent cement with one percent SS-1 emulsion, respectively. Both test sections included PCC drainage layers and HMAC surfacing. Traditional construction equipment was used for the reconstruction of the test sections. No specialized equipment was used for hauling, placement, or compaction. Post construction falling weight deflectometer testing demonstrated the peak surface deflection reduced for both test sections.

The capital cost of virgin granular base were greater that crushed RAP materials due to the increased haul required to transport granular base materials in from pits located outside the city limits.